

**Hanford 200 Areas Spectral Gamma
Baseline Characterization Project**

**216-B-43 to -50, -57, and -61 Cribs
and Adjacent Sites
Waste Site Summary Report**

August 2003



**U.S. Department
of Energy**

GRAND JUNCTION OFFICE

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August 2003

Prepared for
U.S. Department of Energy
Idaho Operations Office
Grand Junction Office
Grand Junction, Colorado

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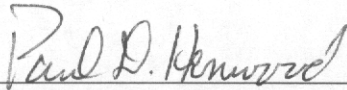
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Project Documents Online: <http://www.gjo.doe.gov/programs/hanf/htfvz.html>

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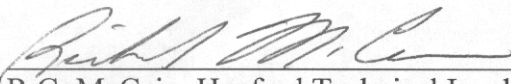
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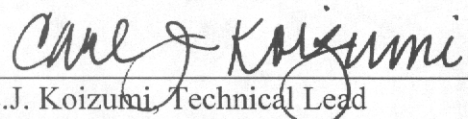
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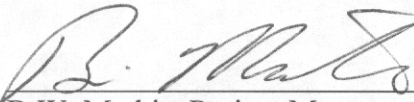
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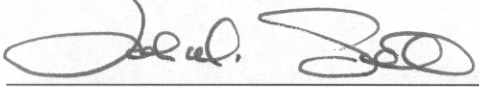
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Executive Summary

The U.S. Department of Energy Richland Office (DOE-RL) tasked the DOE Grand Junction Office (DOE-GJO) to conduct a baseline characterization of the gamma-ray-emitting radionuclides distributed in vadose zone sediments in the vicinity of waste sites in the Central Plateau (200 East and West Areas) of the Hanford Site.

The Spectral Gamma Logging System (SGLS) was used to collect data in existing boreholes and monitoring wells. This system uses a high-purity germanium (HPGe) detector to acquire high-resolution, gamma-energy spectra that allow detection, identification, and quantification of gamma-emitting radionuclides. An equivalent spectral gamma logging system referred to as the Radionuclide Logging System (RLS) was used to acquire log data during 1991 and 1992, the results of which were reported in the *Phase I Remedial Investigation Report for 200-BP-1 Operable Unit* (DOE 1993b). Soil samples were also collected from soil borings and analyzed for radionuclides during that investigation. This report documents SGLS, RLS, and soil sample analytical results obtained from boreholes located north of the BY Tank Farm. This area includes 10 major liquid waste sites designated as the 216-B-43 to -50, -57, and -61 Cribs.

Using spectral gamma logging, cesium-137 (^{137}Cs), cobalt-60 (^{60}Co), antimony-125 (^{125}Sb), and europium-154 (^{154}Eu) were detected in the boreholes and groundwater wells in the vicinity of the 216-B-43 to -50 Crib sites. The predominant contaminant in total activity was ^{137}Cs , which was measured at concentrations up to approximately 10^7 picocuries per gram (pCi/g). In general, ^{137}Cs contamination directly associated with a specific waste site occurs at depths less than 150 feet (ft), although data acquired from two boreholes indicate that ^{137}Cs reached groundwater.

^{60}Co contamination is pervasive with extensive lateral migration throughout the area of the cribs, and ^{60}Co intercepts the groundwater. Soil sample results indicate the gamma emitters ^{60}Co , ^{137}Cs , ^{125}Sb , total uranium (U), non-gamma-emitting radionuclides (strontium-90 [^{90}Sr], technetium-99 [^{99}Tc], and tritium [^3H]), and radionuclides with gamma emissions too weak to routinely detect with the SGLS (plutonium-239 and -240 [$^{239/240}\text{Pu}$]), exist in the high gamma activity zones that extend to a depth of approximately 35 ft. Below the high-activity zones, only ^{137}Cs , ^{60}Co , and ^{99}Tc exist at any significant concentrations in the vadose zone. ^{99}Tc is identified just above the groundwater intercept in two deep boreholes where soil samples were available. ^{99}Tc appears to have followed the same pathway through the vadose zone as ^{60}Co . Although ^{99}Tc , ^{60}Co , and ^{238}U were detected in groundwater in the vicinity of the BY Cribs, no ^{238}U above background concentrations was detected in the vadose zone below a log depth of approximately 60 ft.

Lateral migration of ^{60}Co appears to be extensive. ^{60}Co was detected 220 ft northwest of the 216-B-50 Crib and 286 ft southeast of the 216-B-43 Crib. Contaminant distributions in regions north, west, and south of the cribs could not be assessed because these regions have few boreholes. On the basis of a stratigraphic dip to the north at one degree, it is likely that extensive contamination would be detected north of the cribs. Comparison of borehole logs acquired in 1992 and 2002 indicates continuing migration of ^{60}Co in the area of the cribs.

The 216-B-57 Crib exhibits ^{137}Cs contamination to a maximum elevation of 550 ft (90-ft log depth) in the southern portion of the crib near the influent point of the waste stream. The waste stream (In

Tank Solidification [ITS]) condensate is much different than the tributyl phosphate (TBP) waste disposed of in the 216-B-43 to -49 Cribs. Soil sample analytical results indicate the contaminants $^{239/240}\text{Pu}$, ^{90}Sr , ^{99}Tc , total U, and ^3H are either nonexistent or at very low levels relative to the 216-B-43 to -50 Cribs. Breakthrough of contaminants to the groundwater is not indicated by historical or current gamma measurements. However, soil sample analytical results available from the one deep borehole in the crib indicate ^3H and ^{99}Tc at concentrations less than 1 pCi/g just above the depth of the current groundwater level. ^{60}Co and ^{137}Cs contamination, not continuously detected throughout the vadose zone, are also identified just above and within the groundwater. This contamination is believed to be residual from contaminated groundwater that invaded this area during the disposal of waste in the 216-B-43 to -49 Cribs in 1955.

The 216-B-61 Crib was reportedly not used for waste disposal. Log data and soil sample analytical results corroborate this fact. Measurements of surface soils suggest low-level ^{137}Cs contamination derived from an unknown source.

Recommendations include installing additional boreholes to better define areas of contamination and to assess the possibility that ^{99}Tc follows the same pathways in the vadose zone as ^{60}Co .

1.0 Introduction

The Hanford 200 Areas Spectral Gamma Baseline Characterization Project operates borehole geophysical logging equipment to measure naturally occurring and anthropogenic radionuclides in the subsurface in the vicinity of 200 Area waste sites. The following sections provide brief discussions of background, project purpose and scope, and project objectives.

1.1 Background

The U.S. Department of Energy (DOE) Hanford Site encompasses approximately 1,450 square kilometers (km²) (560 square miles [mi²]) in the Columbia Basin of south central Washington State. Beginning in World War II, the Hanford Site was involved in production of plutonium to support the national nuclear weapons program. The Hanford Site is subdivided into a number of operational regions identified as the 100, 200, 300, and 1100 Areas (Figure 1). In 1989, the U.S. Environmental Protection Agency (EPA) placed these areas on the National Priorities List (NPL) pursuant to the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA). The 200 Areas, located on a plateau near the center of the Hanford Site, consist of the 200 West Area and 200 East Area, which include waste management facilities and inactive irradiated-fuel reprocessing facilities, and the 200 North Area, which was formerly used for interim storage and staging of irradiated fuel.

1.2 Purpose and Scope of Project

The goal of the DOE Grand Junction Office (DOE-GJO) Hanford 200 Areas Spectral Gamma Baseline Characterization Project is to collect data from existing boreholes and determine the present nature and extent of contamination associated with gamma-ray-emitting radionuclides distributed in the subsurface in the vicinity of 200 Area waste sites. The waste sites include liquid waste disposal sites (and associated structures such as pipelines) resulting from the discharge of radioactive liquids from processing facilities to the ground (via ponds, cribs, and ditches), burial grounds, the peripheral regions of the single-shell waste storage tank farms where leakage of high-level radioactive waste constituents from specific tanks may have migrated, and unplanned releases. Most of the liquid waste sites and all of the burial grounds and unplanned release sites have been assigned to the Environmental Restoration (ER) Program. A small percentage of the soil waste sites and the peripheral regions of the tank farms have been assigned to the DOE Office of River Protection (DOE-ORP).

The purpose of the Hanford 200 Areas Spectral Gamma Baseline Characterization Project is to present spectral gamma data and integrate historical data collected from boreholes in and adjacent to waste sites in the Hanford 200 Areas. High-resolution gamma-energy spectra are collected in these boreholes using consistent and defensible methodology. This work effectively extends the existing baseline data set developed for the Hanford single-shell tank farms into the surrounding areas. The baseline data are evaluated to aid in the determination of potential contaminant sources, to develop a dataset that can be used to assess future changes, and to correlate the geophysical signatures of known and presumed geologic features that may affect radionuclide migration within the vadose zone. This information is needed to manage the sites and to make informed decisions about site remediation and accelerated closure actions.

The Spectral Gamma Logging System (SGLS) is used to acquire gamma-ray energy spectra from boreholes and wells related to the 200 Area waste sites. Intervals of high gamma-ray intensity are logged with the High Rate Logging System (HRLS).

Gamma spectra from each borehole are analyzed to determine concentrations of naturally occurring radionuclides potassium-40 (^{40}K), thorium-232 (^{232}Th), uranium-238 (^{238}U), and associated decay progeny, as well as man-made gamma-emitting radionuclides such as cesium-137 (^{137}Cs), cobalt-60 (^{60}Co), and europium-152/154 ($^{152/154}\text{Eu}$). Variations in naturally occurring radionuclides are useful in stratigraphic correlation.

This project is generally limited in scope to passive spectral gamma-ray logging. As a result, only radionuclides that decay with the emission of gamma-ray photons can be detected and quantified. Furthermore, only existing boreholes/wells and any new boreholes drilled for other projects are logged. No new borehole drilling is specified or planned as a part of this project, although recommendations for additional boreholes may be provided when appropriate. Additional details regarding the scope and general approach to this characterization program are included in the baseline characterization plan (DOE 2002c) and project management plan (DOE 2003b).

Specific activities under this project include preparation and maintenance of a database of existing boreholes and geophysical log data, logging existing boreholes with the SGLS and HRLS, analysis and plotting of log data, and preparation of reports. Because many waste sites are the subjects of site characterization efforts in RI/FS work plans, well logging is performed in existing and new boreholes to support these activities, and data are provided for incorporation into the Remedial Investigation Reports.

1.3 Project Objectives

Specific project objectives are:

- To use passive spectral gamma logging to identify the activities of man-made radionuclide contaminants and to estimate current subsurface radionuclide contamination in the vicinity of 200 Area waste sites. Many areas of the subsurface have been contaminated by the disposal of liquid waste to the ground, and, in some cases, by surface spills.
- To identify sources of contamination by measuring the radionuclide contaminant activity in multiple boreholes and correlating data between those boreholes. It is possible, in many cases, to trace the contamination back to probable sources.
- To provide a baseline dataset to help assess ongoing migration of the radionuclides through the vadose zone, and to provide data for the validation and/or determination of initial or boundary conditions of contaminant transport models.
- To generate data that can be used for stratigraphic correlations in 200 Area waste sites. Migration of radionuclides through the vadose zone is affected by differences in composition, porosity, density, and water content. Accurate stratigraphic characterization helps in identifying target-monitoring horizons and in delineating controlling factors in subsurface flow. Lithologic characterization data include vertical profiles of naturally occurring ^{40}K , ^{238}U , and ^{232}Th .

Although the primary focus of this project is interpretation and evaluation of spectral gamma logs, a portion of this project involves assessment of existing data, such as historical gross gamma data, spectral gamma and neutron logs, soil samples, drilling logs, groundwater monitoring information, geology and hydrogeology information, construction details, and operational information. This information is compiled and evaluated with the newly acquired spectral gamma data to understand its significance in relation to the nature and extent of vadose zone contamination. The background and historical information help to identify potential sources of contamination, the date of contamination, rate of contaminant migration (if it occurs), and to explain the nature of the contamination identified by the new spectral gamma log data.

2.0 Spectral Gamma-Ray Logging Methods

The following sections discuss field and technical methods used by the Hanford 200 Areas Spectral Gamma Baseline Characterization Project that have been specifically developed for high-resolution borehole measurements with a sensitivity and accuracy comparable to laboratory equipment.

2.1 Field Methods

Existing boreholes are logged by the SGLS, which uses cryogenically cooled HPGe detectors with an intrinsic efficiency of approximately 35 or 70 percent. A HRLS is used in zones of high gamma activity, where the SGLS detector can become “saturated” and no usable spectra can be acquired. Both detector systems are operated on the same logging vehicle. Each combination of sonde and logging vehicle represents a unique logging system. Two logging vehicles, three SGLS sondes, and one HRLS sonde are available.

SGLS and HRLS log data are collected in accordance with a logging procedure (DOE 2001). Gamma energy spectra are collected in “move-stop-acquire” mode where the sonde is held stationary for measurement and then moved a specified depth increment to the next measurement point. The typical depth increment is 1.0 ft. System gain is adjusted as necessary to maintain a consistent channel relationship for a marker peak (typically the ^{40}K peak at 1461 kilo-electron volts [keV]). Measurement times are selected to detect prominent gamma peaks associated with natural radionuclides (^{40}K , ^{238}U , and ^{232}Th). Depending on casing thickness, typical count times are 100 or 200 seconds (sec) for the SGLS and 300 sec for the HRLS. This results in logging speeds of feet per hour instead of the feet per minute rates common in the petroleum and mineral industries. Verification spectra are collected at the beginning and end of each logging day to monitor system performance, and repeat sections are logged to demonstrate repeatability and consistency.

2.2 Technical Methods

Evaluation of gamma energy spectra provides identification and quantification of naturally occurring and man-made radionuclides on the basis of characteristic energy emissions associated with their decay. Only gamma rays of sufficient energy to penetrate the steel borehole casing and sonde housing can be detected by the SGLS or HRLS. Radionuclides that emit one or more gamma rays at energies between about 150 and 2,800 keV are detectable with the SGLS. The minimum detectable concentration is dependent upon detector efficiency at the appropriate energy, background activity, and the yield (gamma rays emitted, on average, per decay). Factors such as casing, water, shielding,

and the presence of other radionuclides also have an effect. Because waste disposal to the soil column has been discontinued, radionuclides with half lives of less than 1 year have not been detected on the spectral gamma logs and are presumed to have decayed to insignificant levels. Tables 2-1 and 2-2 summarize naturally occurring and man-made radionuclides that can be detected with the SGLS. The terms “primary gamma ray” and “secondary gamma ray” are used to differentiate between the more prominent gamma energy peaks and other, less prominent peaks that may be useful for confirmation. The values indicated in bold are those generally used to calculate concentrations.

Table 2-1. Naturally Occurring Gamma-Emitting Radionuclides

Radionuclide	Primary Gamma Rays			Secondary Gamma Rays		
	Daughter	E (keV)	Y (%)	Daughter	E (keV)	Y (%)
⁴⁰ K		1460.83	10.67			
²³² Th	²¹² Pb	238.63	43.30	²²⁸ Ac	911.21	26.60
	²⁰⁸ Tl	2614.53	35.64	²²⁸ Ac	968.97	16.17
	²⁰⁸ Tl	583.19	30.36	²²⁸ Ac	338.32	11.25
				²⁰⁸ Tl	510.77	8.06
²³⁸ U ¹	²¹⁴ Bi	609.31	44.79	²¹⁴ Pb	295.21	18.50
	²¹⁴ Pb	351.92	35.80	²¹⁴ Bi	1120.29	14.80
	²¹⁴ Bi	1764.49	15.36	²¹⁴ Pb	241.98	7.50
				²¹⁴ Bi	1238.11	5.86
				²¹⁴ Bi	2204.21	4.86
				²¹⁴ Bi	2447.86	1.50

¹ Attainment of secular equilibrium between ²³⁸U and ²¹⁴Bi/²¹⁴Pb requires long time periods on the order of a million years. Activities of both ²¹⁴Bi and ²¹⁴Pb are commonly assumed to be equal to the activity of naturally occurring ²³⁸U. However, these radionuclides are short-term daughter products of ²²²Rn, and accumulations of radon gas inside the casing may temporarily elevate the decay activities of ²¹⁴Bi/²¹⁴Pb relative to the decay activity of ²³⁸U.

Table 2-2. Man-Made Radionuclides

Radionuclide	Half Life (Years)	Primary Gamma Rays		Secondary Gamma Rays	
		E (keV)	Y (%)	E (keV)	Y (%)
⁶⁰ Co	5.2714	1332.50 1173.24	99.98 99.90		
¹⁰⁶ Ru	1.0238	511.86	20.40	621.93	9.93
¹²⁵ Sb	2.7582	427.88	29.60	600.60 635.95 463.37	17.86 11.31 10.49
¹²⁶ Sn	1.E+5	414.50	86.00	666.10 694.80	86.00 82.56
¹³⁴ Cs	2.062	604.70	97.56	795.85	85.44
¹³⁷ Cs	30.07	661.66	85.10		
¹⁵² Eu	13.542	1408.01	20.87	121.78 344.28 964.13 1112.12 778.90	28.42 26.58 14.34 13.54 12.96
¹⁵⁴ Eu	8.593	1274.44	35.19	123.07 723.31 1004.73 873.19	40.79 20.22 18.01 12.27
¹⁵⁵ Eu	4.7611	105.31	21.15		
²³⁵ U	7.038E+08	185.72	57.20	205.31	5.01
^{234m} Pa (²³⁸ U ¹)	4.47E+09	1001.03	0.84	811.00 766.36	0.51 0.29
²³⁷ Np	2.14E+06	312.17	38.60		
²³⁸ Pu	87.7	99.853	0.0074	43.498	0.04
²³⁹ Pu	24110	129.30 375.05 413.71	0.0063 0.0016 0.0015		
²⁴⁰ Pu	6563	104.234	0.007	45.244 160.308	0.045 0.0004
²⁴¹ Pu	14.35	148.567	0.0002	103.68	0.0001
²⁴¹ Am	432.2	59.54 ²	35.90	102.98 335.37 368.05 662.40 722.01	0.02 0.0005 0.0002 0.0004 0.0002

¹ ^{234m}Pa is a short-term daughter of ²³⁸U. Secular equilibrium is achieved relatively quickly. Because of the relatively low gamma yield, this peak is not observed when only background levels of naturally occurring ²³⁸U are present. Hence, the presence of gamma peaks associated with ^{234m}Pa without corresponding peaks associated with ²¹⁴Pb and ²¹⁴Bi indicates the presence of chemically processed uranium.

² The 59.54-keV gamma ray may not be detectable in thick casing.

Other radionuclides of interest, such as tritium (³H), strontium-90 (⁹⁰Sr), and technetium-99 (⁹⁹Tc), are “pure” beta emitters and do not emit any gamma rays that can be detected with the SGLS. However, computer modeling investigations and experience with data interpretation have shown that in the absence of other contaminants, the presence of ⁹⁰Sr at concentrations greater than about 1,000 pCi/g can be inferred from the *bremsstrahlung* generated from interaction of the high-energy beta emissions from ⁹⁰Sr with the steel casing.

Field gamma spectra are processed and analyzed in accordance with a data analysis manual (DOE 2003a). Conventional gamma spectra analysis software is used to detect gamma energy peaks, identify the source radionuclide, and determine the net count rate, counting error, and minimum detectable activity. From the net count rate (P_n , cps) for a specific energy peak, the apparent concentration of the source radionuclide (C_a , pCi/g) is determined by:

$$C_a = \frac{27.027}{Y} \times I(E) \times DTC \times K_c \times K_w \times K_s \times P_n,$$

where Y is the radionuclide yield, $I(E)$ is the logging system calibration function, DTC is the dead time correction, and K_c , K_w , and K_s are energy-dependent correction factors for casing, water, and shielding. The calibration function, $I(E)$, is unique for each combination of sonde and logging vehicle. Values of the calibration function are updated annually and documented in calibration certificates and a calibration report (Koizumi 2002). Concentration error and minimum detectable concentration are calculated using similar equations. The reported concentration error is based on only the estimated counting error. No effort is made to include the effects of errors in the calibration function or correction factors. These errors are discussed in the calibration report (Koizumi 2002). The term “apparent concentration” is used because concentrations are calculated from log data under the assumption that the in situ source distributions are not significantly different from the source distributions in the calibration standards. However, the calibration standards have gamma source distributions that are homogeneous and effectively infinite in spatial extent (with respect to radiation transport), whereas the source distributions in the subsurface may be inhomogeneous and more limited in spatial extent.

The minimum detection level (MDL) of a radionuclide represents the lowest concentration at which the positive identification of a gamma-ray peak for that radionuclide is statistically defensible. A description of the MDL calculation is included in the data analysis manual (DOE 2003a).

For a counting time of 100 sec, the MDL for ^{137}Cs is typically about 0.2 pCi/g. The MDL differs slightly for each spectrum depending upon count time, background activity and concentrations of other radionuclides at the data point, as well as casing thickness. In regions of higher concentrations of man-made radionuclides, the Compton background continuum becomes elevated, increasing the MDL value.

The MDL for ^{60}Co is about 0.15 pCi/g; the MDL for ^{154}Eu is approximately 0.2 pCi/g; and the MDLs for ^{235}U and ^{238}U are approximately 1 and 10 pCi/g, respectively. These values are typical for a 100-sec counting time.

Natural and man-made radionuclide concentrations, total gamma count rate, and dead time are plotted as a function of depth. These plots are included in a Log Data Report that also summarizes borehole construction details, logging conditions, analysis notes, and log plot notes, as well as a brief discussion of results and interpretations. When appropriate, comparison plots with other available logs are also included. Log Data Reports for boreholes in the study area are included in Appendix A on the accompanying CD-ROM.

Log data and geological information from surrounding boreholes are assembled and correlated in an effort to identify contaminated zones and potential sources of contamination. Historical gross

gamma, spectral gamma, and neutron log data are incorporated where available. Three-dimensional geostatistical visualization software is used to interpolate data between boreholes.

A Waste Site Summary Report (WSSR) documents the results of the correlation and evaluation process for each group of waste sites. Waste site groups have been defined in terms of physical proximity and common configuration or operational history. Each WSSR provides a review of background information that includes a description and operational history of the waste sites, a summary of geologic and hydrogeologic conditions, a review of previous investigations, and any existing data such as gross gamma or spectral logs, geologic logs, soil samples, and groundwater analytical data. An assessment and interpretation of the spectral gamma-ray log information are also provided, along with conclusions and recommendations on future data needs or corrective action, where appropriate.

3.0 Background and Physical Setting of the 216-B-43 to -50, -57, and -61 Cribs

Figure 2 is a map of the B-BX-BY Waste Management Area and vicinity that shows the general location of the major waste sites. Figure 3 is a more detailed map of the area. Three major waste sites within the area that have existing boreholes available for evaluation are the 216-B-43 to -50 Cribs, the 216-B-57 Crib, and the 216-B-61 Crib. These cribs are collectively referred to as the BY Cribs. The study area is bounded in the west by the 216-B-57 and -61 Cribs and in the south by the BY Tank Farm. In the north, the study area extends to the northern boundary of the 200 East Area. The eastern boundary was selected to include a deep borehole (299-E33-13) in the area that is not generally associated with a specific waste site but is useful to assess possible impacts by the waste sites and to determine potential sources of contamination.

The information in the following sections was obtained from a variety of sources, including the *Phase I Remedial Investigation Report for 200-BP-1 Operable Unit* (DOE 1993b), *Waste Information Data System (WIDS)*, *System Assessment Capability (SAC)*, Simpson et al. (2001), *B Plant Source Aggregate Area Management Study Report* (DOE 1993a), Brodeur et al. (1993), *Subsurface Conditions Description of the B-BX-BY Waste Management Area* (Wood et al. 2000), *Field Investigation Report for Waste Management Area B-BX-BY* (Knepp 2002), *BY Tank Farm Report* (DOE 1997), and the *Addendum to the BY Tank Farm Report* (DOE 2000b).

3.1 Background of the 200 Areas

Established in 1943, the Hanford Site was originally designed, built, and operated to produce plutonium for nuclear weapons. Uranium metal billets were received in the 300 Area and fabricated into jacketed fuel rods. The fuel rods were loaded into graphite-moderated reactors in the 100 Areas. With the exception of 100-N, which also provided steam to the Hanford Generating Project, these reactors were operated for the sole purpose of producing ^{239}Pu from neutron activation of ^{238}U . The fuel rods were then transported to the 200 Areas, where plutonium and uranium were separated from the residual activation and fission products using a variety of liquid chemical separation processes. The 600 Area includes portions of the Hanford Site not included in the 100, 200, or 300 Areas and

served primarily as transportation corridors and buffer zones between the fabrication, irradiation, and chemical processing areas (DOE 1998).

Chemical separations process facilities were sited in both the 200 East and 200 West Areas. Irradiated fuel rods were temporarily stored in the 200 North Area to allow for decay of short-lived fission products before they were shipped to separations plants. With the startup of the separation plants, high-level wastes containing the bulk of the fission products were discharged to large underground steel tanks, and large quantities of liquid wastes (primarily water) containing minor concentrations of radionuclides and chemicals were discharged to the soil column and percolated into the vadose zone. Depending on contaminant concentrations and a consequent need for isolation, liquid wastes were discharged either to surface ponds and ditches or to underground cribs, reverse wells, trenches, and French drains. These liquid disposal sites were located in the 200 Areas near the processing plants and in the nearby 600 Areas (DOE 1998).

3.2 Geologic Conditions

This section summarizes the geologic setting of the Hanford Site and the B-BX-BY Waste Management Area (WMA). Figure 4 shows the general stratigraphy for the area of the BY Cribs. Lithologic information, used to develop stratigraphy, is obtained from field analysis of sediment samples retrieved during borehole drilling operations and from nearby outcrops. When available, gross gamma-ray logs have been used to support the geologic interpretation. The majority of the boreholes were drilled with a cable tool drill rig, and the samples were obtained from bailings, core barrels, or as retained cuttings, generally from 5-ft intervals. Lindsey and Law (1993), Lindsey et al. (1994), and Wood et al. (2000) presented detailed descriptions and interpretations of the geologic formations near and within the B-BX-BY WMA.

3.2.1 Stratigraphy

Overlying the basalt flows of the Columbia River Basalt Group are the Ringold Formation, the Cold Creek Interval (Plio-Pleistocene unit), the informal Hanford formation, and Holocene-Age deposits. Rockwell (1979), Reidel et al. (1992), Delaney et al. (1991), Lindsey (1991), Lindsey et al. (1994), and Bjornstad et al. (2002) have presented extensive descriptions and discussions of these formations. Bjornstad et al. (2002) formalized the stratigraphic nomenclature for post-Ringold sediments at the Hanford Site, and this nomenclature is used in this report.

3.2.1.1 Columbia River Basalt Group

The Columbia River Basalt Group consists of 174,000 cubic kilometers (km³) of tholeiitic flood-basalt flows that erupted between 17 and 6 million years ago and cover approximately 164,000 km² of eastern Washington, Oregon, and western Idaho (Reidel et al. 1989). The distribution of the basalt flows reflects the tectonic history of the area (Reidel et al. 1989). The basalt may approximate 4,000 meters (m) in thickness underlying the Hanford Site (Reidel et al. 1989; Glover 1985). The uppermost basalt flow, the Elephant Mountain Member, is at an elevation of about 390 ft under the waste sites. Reidel et al. (1989), Reidel and Fecht (1981), and Rockwell (1979) presented additional information about the Columbia River Basalt Group.

3.2.1.2 Ringold Formation

Ringold sediments predominantly consist of layers of fluvial sand, ancient soils (paleosols), and lacustrine sand, silt, and clay (Lindsey 1996). This formation may be as much as 600 ft thick across the Hanford Site. It consists of uncemented to locally well-cemented clay, silt, fine- to coarse-grained sand, and pebble-to-cobble conglomerate. Ringold sediments are absent underneath the study area (Williams et al. 2000).

3.2.1.3 Cold Creek Unit (Plio-Pleistocene)

The Cold Creek Unit sediments unconformably overlie the Ringold Formation. This unit is laterally discontinuous. Plio-Pleistocene sediments, which are absent in the vicinity of the study area (Williams et al. 2000), consist of locally derived basaltic alluvium and pedogenic calcium-carbonate-rich material. The basaltic material consists of weathered and unweathered locally derived basaltic gravel containing varying amounts of sand and silt. The carbonate-rich sediments consist of calcium carbonate cemented silt, sand, and gravel interfingering with carbonate-poor sediments. Both of these facies may be present at some locations. Bjornstad et al. (2002) have named these sediments the Cold Creek Unit.

In the past, the Plio-Pleistocene was divided into an upper silty sand to sandy silt that was designated as early Palouse soil and a lower calcium carbonate-rich interval often referred to as the “caliche layer” (Lindsey et al. 2000). Numerous investigations conducted in the 1990s have observed that the upper unit contains stratified fine sand indicative of lacustrine deposition and not eolian conditions associated with the early Palouse soil (Lindsey et al. 2000). The Cold Creek Unit also contains a series of paleosols with calcium carbonate development indicative of an arid environment (Slate 1996).

The pre-Missoula gravel consists of quartzose to gneissic clast-supported pebble to cobble gravel with quartzo-feldspathic sand matrix that underlies the Hanford formation in the east-central region of the Cold Creek syncline and at the east end of Gable Mountain anticline east and south of the 200 East Area (Williams et al. 2000).

The Early Palouse soil is a compact, massive loess-like silt with minor fine-grained sand unit that may overlie the Plio-Pleistocene unit. This unit is designated the "Early Palouse soil," and it can range up to tens of feet thick. The Early Palouse sediments can grade upward into sediments similar to those at the base of the overlying Hanford formation, making the contact between these two lithologic units difficult to distinguish. The Early Palouse soil is thickest in the southwest and southeast portions of the 200 West Area, where it reaches a maximum thickness of 65 ft.

3.2.1.4 Hanford Formation

A series of Pleistocene catastrophic flood deposits, informally known as the Hanford formation, overlies the Plio-Pleistocene and older sediments throughout the Hanford Site. The Hanford formation consists of gravel, sand, and silt. The sediments of the Hanford formation are unconsolidated, uncemented, and highly transmissive for the flow of water. This formation is thickest in the central part of the Hanford Site, with a maximum thickness of 350 ft. The Hanford formation is divided into three facies (gravel-dominated, sand-dominated, and silt-dominated) that

are gradational with each other. Bjornstad et al. (2002), Lindsey (1991), Reidel et al. (1992), and Wood et al. (2000) provided detailed discussions of the Hanford formation lithology.

Interpretations of sediment samples obtained from boreholes in the 200 Areas (Lindsey and Law [1993]; Lindsey et al. [1994]; and Reidel et al. [1992]) have resulted in subdividing the Hanford formation into units (H1a, H1, H2, H2a, H3, and H4). Units H1a, H2a, H3, and H4 are laterally discontinuous, and H3 and H4 are locally identified at the base of the formation (Lindsey et al. 2000). Hanford H4 is absent in the 200 East Area.

The rhythmite facies sediments (Hanford H4) were deposited under slack water conditions and in back-flooded areas remote from the main flood channel. These sediments consist of thinly bedded, plane-laminated and ripple cross-laminated silt and fine- to coarse-grained sand, and commonly display a normally graded rhythmite sequence a few centimeters to several tens of centimeters thick (Baker et al. 1991; DOE 1988). This facies dominates the Hanford formation along the western, southern, and northern margins of the Pasco Basin, within and south of the 200 Areas.

The Hanford H3 unit is a coarse-grained unit that consists of pebble and cobble gravel with interbedded sand deposited by high-energy floodwaters in or immediately adjacent to the main flood channel. The H3 generally consists of coarse-grained basaltic sand and granule to boulder gravel and ranges from well sorted to poorly sorted. In outcrop, these sediments display massive bedding, planar to low-angle bedding, and large-scale planar cross bedding.

The Hanford H2 unit is about 180 to 190 ft thick and consists of sand-dominated facies with interbedded silt lenses (Lindsay and Law 1993; Lindsey et al. 1994). Some laterally discontinuous silt-rich interbeds are reported, and these high-silt content zones may have higher moisture content and CaCO_3 content than the surrounding sand-dominated material. The depositional facies are discontinuous in both horizontal and vertical extents, and little correlation between boreholes has been possible in terms of the minor differences between such features as the silty sand and sandy silt layers (Lindsay and Law 1993; Lindsey et al. 1994).

Unit H1 is dominated by coarse to granule sand and lesser pebble gravel formed from a complex interfingering of gravel and sand-dominated facies (Lindsay and Law 1993; Lindsey et al. 1994). The relative abundance of gravelly facies decreases from the northwest to the south. As gravel content decreases, unit H1 interfingers with the more sand-rich strata of unit H2.

Clastic dikes consisting of layers of silt, sand, and granule gravel crosscut the Hanford formation. These clastic dikes generally crosscut the bedding as alternating vertical to subvertical dikes, although they may locally run parallel to bedding. Clastic dikes also occur in the older sediments (Fecht et al. 1999).

3.2.1.5 Holocene Surficial Deposits

Holocene surficial deposits consist of a mix of silt, sand, and gravel deposited by a combination of eolian and alluvial processes (DOE 1988).

3.2.2 Structure

The Hanford Site is located in the Pasco Basin, which is a physical and structural depression in the Columbia Plateau created by tectonic activity and folding of the Columbia River basalts. The

structural framework of the Pasco Basin began developing before Columbia River Basalt Group volcanism (Reidel et al. 1994) and was an area of subsidence that accumulated thick deposits of sediments and volcanic rock. This pattern continued through Columbia River Basalt Group volcanism. Anticlinal ridges were growing under north-south compression. This compression resulted in a series of anticlinal ridges and synclinal valleys with a general east-west trend. The north-south compression and east-west extension have persisted from at least the middle Miocene to the present (Hooper and Camp [1981]; Reidel [1984]; Hooper and Conrey [1989]; Reidel et al. [1989]).

The geologic structure of the Pasco Basin area is dominated by a series of east-west-trending anticlines and synclines. Anticlines to the north and south create topographic high areas (Gable Mountain and Rattlesnake Mountain, respectively) with outcropping basalt flows. The Hanford Site 200 Areas are situated on the northern limb of the Cold Creek syncline where bedrock dips to the south at an angle of approximately 5 degrees. Approximately 270 ft of sediments overlie the dipping basalt bedrock in the vicinity of the site.

3.3 Hydrology

Hartman et al. (2003), Narbutovskih (1998), and Narbutovskih (2000) described the hydrogeology of the Hanford Site and the B-BX-BY WMA. Considerable uncertainty currently exists regarding both velocity and direction of groundwater flow in certain regions of the 200 East Area in the vicinity of the B-BX-BY WMA. The hydraulic gradient is nearly flat. Flow directions were estimated at the WMA using in situ flow techniques such as the colloidal boroscope. In situ flow measurements indicate that the area under the BY Cribs and the BY Tank Farm has a low flow rate that is close to stagnant. Presently, the unconfined aquifer in the area is less than 10 ft thick and decreasing approximately 7 in. a year. The top of the unconfined aquifer is currently at an elevation of approximately 401 ft (122.2 m). The base of the unconfined aquifer is believed to be the top of a hummocky basalt surface with structural relief that varies from 5 to 11 ft.

Groundwater contamination currently exists underneath the BY Cribs. The BY Cribs were closed to waste disposal due to an elevated ^{137}Cs concentration in the groundwater of the 241-BY-11 (currently designated as 299-E33-03) well (Figure 5) on January 9, 1956 (Thomas et al. 1956). A groundwater sample collected in February 1956 from well number 241-BY-12 (currently 299-E33-04) identified a contaminant that had not been previously identified. This contaminant, which was determined to be ^{60}Co , exceeded the limits for groundwater contamination in 1956 by a factor of three hundred. A well (currently 299-E33-17) located about 1,000 ft southeast from the BY Cribs site was also contaminated but the concentrations were below the limits. It was determined the total volume of waste disposed of at the BY Cribs would have been reduced by approximately 50 percent if it had been known earlier that ^{60}Co existed in the groundwater (Thomas et al. 1956).

Currently, a groundwater contamination plume containing high levels of nitrate, cyanide, ^{60}Co , and ^{99}Tc lies under the BY Cribs (Hartman et al. 2003). These contaminants extend from the BY Cribs to the north, westward to the northeast corner of the Low-Level Waste Management Area 1, and south to the north portion of the BY Tank Farm, where only cyanide and ^{60}Co have been detected. Uranium was also detected in the groundwater in the south portion of the BY Cribs.

3.4 Description of the 216-B-43 to -50, -57, and -61 Cribs and Adjacent Sites

Several facilities into which millions of gallons of liquid waste and wastewater were discharged to the soil column are located in this study area. Major waste sites include the 216-B-43 to -50 Cribs and the 216-B-57 Crib. The 216-B-61 Crib was constructed but apparently never used. Another facility in the area that may have had an impact to the vadose zone is the 216-BY-201 Settling Tank. Unplanned Releases designated 200-E-9, -89, -144 also occurred within the area. The boundaries of the study area were chosen to include the deep boreholes and/or groundwater monitoring wells in the vicinity of the waste sites and to include the first row of tanks from the BY Tank Farm. A brief discussion of each site or unplanned release is included in the following sections. Figure 3 provides the location of each site.

The 216-B-43 to -50 Cribs are located approximately 200 ft north of the BY Tank Farm. Figure 6 shows views of the area overlying the 216-B-43 to -50 Cribs and associated boreholes. Each of the eight cribs were constructed of four 4-ft-diameter by 4-ft-long concrete culverts buried vertically, 7 ft below grade, on a 5-ft-thick bed of gravel (Figure 7). The culverts are arranged in a square pattern with the centers spaced 15 ft apart in a 30-ft by 30-ft by 15-ft -deep excavation. Each culvert is fed by an 8-in. steel pipe coming from a main in a chevron pattern. Each culvert has a concrete cover.

The pipelines to the cribs were blanked when disposal to the cribs was terminated in 1956 due to the existence of elevated ^{137}Cs contamination in the groundwater. The crib vent risers were cut and blanked 1.5 ft below the ground surface. The surface above and near the units was covered with 10-mil plastic. The plastic was covered with 6 in. of sand and 12 in. of topsoil. This area was fertilized with 60 pounds/acre of 16-20-0 fertilizer and seeded with 20 pounds/acre of cheatgrass. The remainder of the ground surface within the radiation zone was seeded with cheatgrass and Siberian wheatgrass.

The 216-B-50 Crib received condensate from the BY Tank Farm In Tank Solidification (ITS) system, located in the BY Tank Farm. The crib was originally constructed along with seven others (216-B-43 to -49) in the same location to receive scavenged tributyl phosphate (TBP) waste. The other seven were used for this purpose, but taken out of service when a ^{60}Co and ^{137}Cs contamination breakthrough to groundwater occurred in 1956. The decision to use the 216-B-50 Crib for ITS condensate was made about 8 or 9 years later when monitoring showed that the groundwater radioactivity levels were definitely decreasing (WIDS).

During construction, the 216-B-57 Crib was filled to 4 ft above the bottom with gravel (approximately 620 cubic yards). A perforated, 12-in. corrugated pipe runs the length of the crib, 3 ft above the bottom. The side slope of the original crib construction is 1.5:1. In 1991, characterization boreholes were drilled and sampled to determine the nature and extent of the contamination. The beginning date for this crib was February 1968 and the end date June 1973. In 1994, the site was covered with an engineered barrier known as the Hanford Prototype Barrier. The barrier is 340 ft long, 210 ft wide, and attains a maximum height of 49 ft above the original ground surface. The total surface area of the barrier is 6.2 acres.

The 216-B-61 Crib was built to receive intermediate level process condensate from the ITS unit when the 216-B-50 Crib reached its radionuclide capacity. However, available records indicate that the 216-B-61 Crib was never used.

The 216-BY-201 Flush Tank received TBP waste via the BY Tank Farm that was subsequently released to the 216-B-43 to -49 Cribs. The flush tank is a rectangular, reinforced concrete disposal structure. The unit was designed to scavenge the TBP waste and discharge the supernatant to the 216-B-43 to -49 Cribs. The tank contained a vent pipe 0.5 ft in diameter by 9 ft long that extended from the top of the tank to 4 ft above grade, and a 0.5-ft-diameter by 7-ft-long pipe that extended from the top of the tank to 2 ft above grade. The tank is constructed of concrete. A manhole is located at each end of the tank. A 4-in.-diameter pipe from the BY Tank Farm enters near the top of the tank. A "Miller Siphon" (manufactured by Pacific Flush Tank Company) is located at the bottom of the tank and drained waste through a 14-in. line, north to the 216-B-43 to -49 Cribs. An overflow pipe is also connected to this line.

On September 15, 1955, approximately 11,000 gal of TBP supernate waste overflowed from the 241-BY-201 Flush Tank and ran over the ground, northeast toward the 216-B-43 Crib (UPR-9). Most of the contamination was pushed into a shallow area southeast of the 216-B-43 Crib and covered with 2 ft of clean dirt. The contamination left near the flush tank was covered with 10 ft of clean soil.

The 200-UPR-89 site is located north of the BY Tank Farm. In 1991, contaminated soil was consolidated on top of the 216-B-43 to -50 Cribs and stabilized with a layer of clean dirt. The site also includes an irregularly shaped drill pad area and a contaminated concrete pad that were also covered with clean dirt. All of the stabilized areas of UPR-200-E-89 were zoned off and posted with "Underground Radioactive Material" signs.

3.5 Operational History

The BY Tank Farm complex received waste generated by a variety of major chemical processing operations. Wood et al. (2000) provided a discussion of the operations and wastes transferred to selected waste sites in the study area. Table 3-1 provides a general summary of the sites and associated wastes, and Table 3-2 presents an estimate of releases of various radionuclides.

Table 3-1. Summary of the Operational History for the 216-BY Cribs

Site	Time in Use	Mean Estimate of Volume (m ³)	Type of Waste
216-B-43 Crib	Nov. 1954	2,100	Scavenged uranium recovery from U Plant
216-B-44 Crib	Dec. 1954 - Mar. 1955	5,600	
216-B-45 Crib	Apr.-June 1955	4,910	
216-B-46 Crib	Sept.-Dec. 1955	6,700	
216-B-47 Crib	Sept. 1955	3,700	
216-B-48 Crib	Nov. 1955	4,090	
216-B-49 Crib	Nov.-Dec. 1955	6,700	
216-B-50 Crib	Jan. 1965-1974	54,800 DOE (1993a)	Storage tank condensate from ITS-1 unit from BY Tank Farm
216-B-57 Crib	Feb. 1968-June 1973	84,400 DOE (1993a)	Storage tank condensate from ITS-2 unit from BY Tank Farm
216-B-61 Crib	Not used		
241-BY-201	Unknown	11,000 gal spill (WIDS)	Scavenged uranium recovery from U Plant
References:	WIDS	Bergeron et al. (2001)	Waite (1991)

Table 3-2. Summary of Mean Radionuclide Release Estimates for the 216-BY Cribs

Crib	¹³⁷ Cs (Mean Estimate in Curies)	³ H (Mean Estimate in Curies)	⁶⁰ Co (Mean Estimate in Curies)	U (Total) (Mean Estimate in kg)	⁹⁰ Sr (Mean Estimate in Curies)	⁹⁹ Tc (Mean Estimate in Curies)	²³⁹ Pu (Mean Estimate in Curies)
216-B-43	1340	10.6	0.0003	140	1320	10.2	1.21
216-B-44	3690	28.3	0.0007	376	3610	27.3	3.27
216-B-45	3190	24.7	0.0007	327	3140	23.8	2.82
216-B-46	4460	33.8	0.0009	450	4310	32.6	3.90
216-B-47	2400	18.7	0.0005	246	2330	18.0	2.13
216-B-48	2540	20.7	0.0005	270	2480	20.0	2.31
216-B-49	4260	33.8	0.0009	447	4140	32.6	3.82
216-B-50	Not available – Not estimated in Simpson et al. (2001)						
216-B-57	Not available – Not estimated in Simpson et al. (2001)						
216-B-61	None						
Reference:		Simpson et al. (2001). Radionuclides are decayed to January 1, 1994.					

3.6 Previous Investigations

Several investigations have been conducted in the vicinity of the BY Cribs. Initially, geophysical logging with gross gamma detectors was utilized to provide a visual comparison of gross gamma log profiles over time. These logs can be useful to determine if contamination has moved downward or changed in intensity. Due to the relatively poor spatial resolution of the data (1 ft) and depth registration errors, tabulation of the maximum spatial peak count rates and comparison of those count rates over time are not recommended. Small changes in the position of the borehole probe between loggings cause large variations in the spatial peak count rates. Only by qualitatively reviewing changing trends in the temporal data is it possible to identify actual changes in the

formation contamination concentration. The frequency of gross gamma logging is variable in boreholes such that a statistical analysis of trends is not recommended. Geophysical logging of monitoring wells and boreholes was conducted as early as 1957 at the facilities related to B Plant operations. Several subsequent evaluations of the log data were performed, including Raymond and McGhan (1964) and Fecht et al. (1977), which are described in this section.

Raymond and McGhan (1964) provided gross gamma logs from a scintillation detector in “representative wells adjacent to waste disposal sites. Logs of wells that show no ground contamination are not included.” The scintillation detector system had a lower detection limit reported as about 3 pCi/cc (^{106}Ru - ^{106}Rh). Log data between 1957 and 1974 were acquired with a similar detection system but with at least three modifications. These modifications were generally to improve system sensitivity and to reduce noise. The profile of the gamma count rate is not changed significantly by these modifications, so that comparisons over time may be made. Recorder chart data may have been transferred to logarithmic graph paper to account for required scale changes needed to accommodate wide variations in gamma activity encountered during logging, which made direct observation and interpretation somewhat difficult.

Previous investigators have provided general assessments of the major waste sites (216-B-43 to -50 Cribs, 216-B-57 Crib, and the 216-B-61 Crib), where relatively closely spaced boreholes have been drilled. Another borehole (299-E33-13) in the area has been drilled to about 260 ft to assess the deep vadose zone and/or the groundwater east of the cribs.

DOE (1993a) provided comprehensive descriptions of these studies, a discussion of gross gamma logging methodology, and interpretations of the data. DOE (1993a) also presented an evaluation of individual waste units such as cribs, ponds, trenches, and ditches. Brodeur et al. (1993) provided summaries of several waste units that included waste discharge histories, plan views of the sites, and geophysical log data acquired in the monitoring boreholes.

Borehole logs acquired in 1959 and 1963 in 299-E33-04 and -07 (Figures 8 and 9, respectively) were included as representative of the 216-BY Cribs (Raymond and McGhan 1964). The 1959 log for borehole 299-E33-04 showed the entire soil column was highly contaminated to the bottom of the borehole, and borehole 299-E33-07 was contaminated from 10 to 160 ft below ground surface and at the bottom of the borehole. Note: Borehole 299-E33-07 is adjacent to the 216-B-50 Crib, which did not receive waste until 1965, approximately 10 years after waste was introduced into the 216-B-43 through -49 Cribs. The 1963 logs indicated significant decay of radionuclides between 1959 and 1963.

Fecht et al. (1977) evaluated the historical gross gamma-ray logs acquired between 1954 and 1973 and compared these logs to data collected in 1976 with a new logging system. The original equipment was replaced in 1974 with a system that increased the lower limit sensitivity by approximately a factor of three over the former system (Fecht et al. 1977). Data were normalized to adjust the background level of the pre-1976 logs to the 1976 values to allow easier, “direct” comparison of the various logs.

Table 3-3. Boreholes Evaluated by Fecht et al. (1977)

Borehole	Crib	Logs Evaluated	Depth of Contamination	Breakthrough to Water
299-E33-1A	216-B-43	1959, 1963, 1968, 1976	23 ft – water table	“Could have”
299-E33-02	216-B-44	1959, 1963, 1970, 1976	42 ft – water table	“Could have”
299-E33-03	216-B-45	1959, 1963, 1970, 1976	26 ft – water table	“Could have”
299-E33-22	216-B-45	1965, 1976	0 ft – water table	“Could have”
299-E33-04	216-B-46	1959, 1963, 1970, 1976	7 ft – water table	“Could have”
299-E33-23	216-B-46	1965, 1970, 1976	7 ft – water table	“Could have”
299-E33-05	216-B-47	1959, 1963, 1970, 1976	40 ft – 122 ft	No
299-E33-06	216-B-48	1959, 1963, 1970, 1976	11 ft – 152 ft	“Could have”
299-E33-07	216-B-50	1959, 1968, 1976	10 ft – water table	“Could have”
299-E33-24	216-B-57	1968, 1970, 1975	25 ft – 65 ft	No
299-E33-25	216-B-61	1970, 1976	Low-level at surface contaminants	No
299-E33-26	216-B-61	1976	Low-level contaminants	No

Data acquired from two boreholes exhibit interesting changes prior to 1976. Boreholes 299-E33-22 (Figure 10) and 299-E33-23 (Figure 11) show an influx of contamination between 1965 and 1976. Current SGLS measurements in these boreholes indicate ^{137}Cs contamination extending from a depth near the ground surface to groundwater with minor amounts of ^{154}Eu and ^{60}Co . The only active crib in the area at this time was the 216-B-50 Crib, which began receiving waste in 1965. Borehole 299-E33-22 is approximately 30 ft away from borehole 299-E33-03, in which high ^{137}Cs concentrations were detected in groundwater in 1956, causing the BY Crib disposal activities to be terminated.

Borehole 299-E33-07 indicated contamination between log depths of 100 and 160 ft in 1959 (Figure 9) prior to the initiation of waste disposal in the 216-B-50 Crib in 1965. Contamination extended to groundwater by the 1976 log date. Fecht et al. (1977) suggested the contamination above 160 ft in log depth had “migrated laterally from waste discharges from the 216-B-45, -46, and -49 cribs.”

Brodeur et al. (1993) evaluated the 216-B-57 and 216-B-61 Cribs using logs acquired for the *B Plant Source Aggregate Area Management Study Report* (DOE 1993a) and the 200-BP-1 remedial investigation (DOE 1993b). Boreholes evaluated included 299-E33-24, -304, -305, and -306 for the 216-B-57 Crib and 299-E33-25 and -26 for the 216-B-61 Crib. An evaluation was not conducted for the 216-B-43 through -50 Cribs.

Brodeur et al. (1993) determined a high ^{137}Cs contamination zone exists between the 30- and 60-ft log depth that is a result of effluent released in the 216-B-57 Crib, and very little migration of contaminants has occurred since the site was closed. Brodeur et al. (1993) stated the ^{137}Cs and ^{60}Co contamination that occurs in borehole 299-E33-24 just above the groundwater in the vadose zone and within the groundwater migrated to this location from another site. No comparisons of the spectral gamma logs with soil samples were made in the report. An evaluation of the geophysical logs from the vicinity of the 216-B-61 Crib suggested near-surface contamination and deep ^{60}Co contamination in the area of groundwater. Brodeur et al. (1993) stated the deep contamination was carried by the groundwater to the location from another site.

Geophysical logging was performed in 27 boreholes in the 216-B-43 through 50 Crib and the 216-B-57 and -61 Crib by Westinghouse Hanford Company during 1991 and 1992 using the Radionuclide Logging System (RLS). A description of the activity and the results of the surveys are presented in Price (1992) and summarized in DOE (1993b). These geophysical logs have been compared to current SGLS log results and plotted with soil sample analytical results from the BP-1 investigation (see Section 4.0, "SGLS Logging Results").

Szwartz (1996) summarized results of geophysical logging in four shallow (e.g., < 50 ft) characterization boreholes drilled into the 216-B-57 Crib in 1993. The logging results suggested minor (i.e., < 4 pCi/g) ^{137}Cs contamination near the ground surface; one borehole exhibited a maximum ^{137}Cs concentration of 3 pCi/g at a depth of 32 ft. This detection of ^{137}Cs approximately 72 ft west of the influent point near the center of the crib was believed to be "a product of horizontal migration from the 216-B-57 Crib."

In 1992, a Phase I Remedial Investigation for the BP-1 Operable Unit (DOE 1993b) was conducted that included extensive soil borings, geophysical logging, and collection of soil samples. These data are summarized in Section 4.0, "SGLS Logging Results." This study concluded that contamination was generally confined to the area beneath the cribs and that significant lateral migration due to perched groundwater conditions did not appear to have occurred. Below 50 ft, concentration levels were observed to decline until a depth of 100 ft, at which concentrations remained uniformly low throughout the remainder of the vadose zone.

4.0 SGLS Logging Results

This section details the data available acquired from boreholes within the study area. Log plots and Log Data Reports for these boreholes (Appendix A on accompanying CD-ROM) were previously released and are available on the Internet at <http://www.gjo.doe.gov/programs/hanf/HTFVZ.html>.

4.1 Boreholes and Wells Logged

Available data include historical gross gamma logs, RLS data, soil sample analytical results, and SGLS data. Table 4-1 lists the boreholes and groundwater wells indicating the type of data available for this investigation.

Figure 3 shows the locations of boreholes and wells used in the vadose zone characterization efforts for the study area. In Table 4-1, the boreholes and groundwater wells are associated with specific liquid waste disposal sites based on their proximity. Also included in the table are the dates the

boreholes were drilled, type of data reviewed for this characterization, the depth intervals (elevation) logged with the SGLS, and specific radionuclides that were detected either by logging or from soil samples.

Table 4-1. Boreholes and Groundwater Monitoring Wells Reviewed During the Investigation of the 216-BY Cribs

Borehole	Date Drilled	Most Current Data Available for Review	Borehole Depth /Elevation (ft)	Radionuclides Detected
299-E33-1A	Aug. 1954	RLS, SGLS	239.0/396.4	¹³⁷ Cs, ⁶⁰ Co
299-E33-296 (abandoned)	Mar. 1992	RLS, soils	221.5/410.8	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ⁹⁹ Tc, total U, ³ H
299-E33-314 (abandoned)	May 1992	Soils	30.5/601.8	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ⁹⁹ Tc, ³ H
299-E33-315 (abandoned)	Apr. 1992	Soils	31.5/600.6	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, total U, ³ H
299-E33-02	Nov. 1954	RLS, SGLS	238.0/397.1	¹³⁷ Cs, ⁶⁰ Co, ¹⁵⁴ Eu
299-E33-297 (abandoned)	Mar. 1992	RLS, soils	33.0/599.8	¹³⁷ Cs, ⁶⁰ Co, ¹⁵⁴ Eu, ⁹⁰ Sr, ^{239/240} Pu, ⁹⁹ Tc, total U, ³ H
299-E33-316 (abandoned)	Mar. 1992	Soils	31.5/600.8	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H
299-E33-317 (abandoned)	Apr. 1992	Soils	31.5/600.9	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ⁹⁹ Tc, total U, ³ H
299-E33-336	Unknown	SGLS	143.9/483.2	¹³⁷ Cs, ⁶⁰ Co, ¹²⁵ Sb
299-E33-03	Nov. 1954	RLS, SGLS	243.0/391.0	¹³⁷ Cs, ⁶⁰ Co, ¹⁵⁴ Eu, ¹²⁵ Sb
299-E33-22	Aug. 1965	RLS, SGLS	235.0/399.5	¹³⁷ Cs, ⁶⁰ Co, ¹⁵⁴ Eu
299-E33-298 (abandoned)	Apr. 1992	RLS, soils	29.5/602.0	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc
299-E33-318 (abandoned)	Jan. 1992	Soils	30.0/600.9	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc
299-E33-319 (abandoned)	Apr. 1992	Soils	29.5/601.8	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc
299-E33-04	Dec. 1954	RLS, SGLS	233.0/400.2	¹³⁷ Cs, ⁶⁰ Co
299-E33-23	Sept. 1965	RLS, SGLS	232.0/400.6	¹³⁷ Cs, ⁶⁰ Co
299-E33-299 (abandoned)	Feb. 1992	RLS, soils	35.0/595.8	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc, ¹²⁵ Sb
299-E33-310 (abandoned)	Dec. 1991	RLS, soils	32.0/597.8	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ¹²⁵ Sb
299-E33-311 (abandoned)	Mar. 1992	RLS, soils	29.5/600.9	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc, ¹²⁵ Sb
299-E33-05	June 1965	RLS, SGLS	243.0/395.8	¹³⁷ Cs, ⁶⁰ Co, ¹²⁵ Sb
299-E33-38	Feb. 1991	RLS, SGLS	242.0/393.3	¹³⁷ Cs, ⁶⁰ Co
299-E33-300 (abandoned)	May 1992	RLS, soils	34.0/601.3	¹³⁷ Cs, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U

Borehole	Date Drilled	Most Current Data Available for Review	Borehole Depth /Elevation (ft)	Radionuclides Detected
299-E33-320 (abandoned)	May 1992	Soils	35.0/598.1	¹³⁷ Cs, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc
299-E33-321 (abandoned)	May 1992	Soils	33.5/601.7	¹³⁷ Cs, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U
299-E33-301 (abandoned)	Apr. 1992	Soils	35.0/597.5	¹³⁷ Cs, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U
299-E33-322 (abandoned)	Apr. 1992	Soils	30.5/601.7	¹³⁷ Cs, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc
299-E33-323 (abandoned)	May 1992	Soils	31.5/601.5	¹³⁷ Cs, ⁹⁰ Sr, ^{239/240} Pu, ⁶⁰ Co, total U, ⁹⁹ Tc
299-E33-06	June 1965	SGLS	241.5/386.7	¹³⁷ Cs, ⁶⁰ Co
299-E33-302 (abandoned)	Jan. 1992	RLS, soils	220.2/408.5	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ³ H, total U, ⁹⁹ Tc, ¹²⁵ Sb
299-E33-312 (abandoned)	Dec. 1991	RLS, soils	28.3/600.4	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc, ¹²⁵ Sb
299-E33-313 (abandoned)	Apr. 1992	Soils	29.5/599.4	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H, total U, ⁹⁹ Tc, ¹²⁵ Sb
299-E33-07	Apr. 1955	RLS, SGLS	234.0/397.2	¹³⁷ Cs, ⁶⁰ Co, ¹⁵⁴ Eu
299-E33-303 (abandoned)	Oct. 1991	RLS, soils	29.2/599.1	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, total U, ¹²⁵ Sb
299-E33-308 (abandoned)	Dec. 1991	RLS, soils	23.5/604.9	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ^{239/240} Pu, ³ H
299-E33-309 (abandoned)	Oct. 1991	RLS, soils	30.5/598.2	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ⁹⁹ Tc, total U, ¹²⁵ Sb
299-E33-40	Apr. 1991	RLS, SGLS	318.0/313.0	¹³⁷ Cs, ⁶⁰ Co
299-E33-24	May 1967	RLS	246.7/394.61	¹³⁷ Cs, ⁶⁰ Co
299-E33-304 (abandoned)	Oct. 1991	RLS, soils	230.5/409.7	¹³⁷ Cs, ⁶⁰ Co, ⁹⁰ Sr, ⁹⁹ Tc, total U, ³ H
299-E33-305 (abandoned)	Sept. 1991	RLS, soils	50.0/589.5	¹³⁷ Cs, ⁹⁰ Sr, ⁹⁹ Tc, total U
299-E33-306 (abandoned)	Sept. 1991	Soils	50.0/587.9	¹³⁷ Cs, total U
299-E33-25	Feb. 1969	SGLS	232/402.3	¹³⁷ Cs, ⁶⁰ Co
299-E33-26	Mar. 1969	SGLS	239.5/396.6	¹³⁷ Cs, ⁶⁰ Co
299-E33-307	May 1991	RLS, soils	26.0/603.0	¹³⁷ Cs
299-E33-13	Oct. 1953	RLS, SGLS	236.0/395.7	¹³⁷ Cs, ⁶⁰ Co
299-E33-90 (abandoned)	Sept. 1965	Gross gamma	140.0/483.0	Possible ¹³⁷ Cs and ⁶⁰ Co
299-E33-91 (abandoned)	Aug. 1965	Gross gamma	140.0/483.0	Possible ¹³⁷ Cs and ⁶⁰ Co

Historical borehole logs were reviewed, and the summary by Fecht et al. (1977) included in Section 3.0 adequately described findings for these boreholes. Two additional boreholes (299-E33-90 and -91) located east of the 216-B-43 to -50 Cribs were drilled and logged in 1965. The boreholes were subsequently abandoned at an unknown date. Gross gamma logs acquired by

Pacific Northwest Laboratory (PNL) and digitized by Stoller are presented and discussed in Section 5.0, "Interpretation of Results."

Data were collected for site characterization in and adjacent to the cribs in 1991 and 1992 to support the remedial investigation process (DOE 1993b). Three boreholes were drilled in each of the 216-B-43 to -50 Cribs (see Figure 12), three in the 216-B-57 Crib, and one in the 216-B-61 Crib. Soil samples were collected in the 28 boreholes and analyzed for radionuclides. Of the 28 boreholes, 17 were logged with the RLS. All of these boreholes were abandoned upon completion of the characterization effort.

In addition, seven boreholes that existed in the crib area prior to the 1991 characterization were logged with the RLS. These seven boreholes were also logged with the SGLS in 2001. Six other boreholes in the area, not logged with the RLS in 1991, were logged with the SGLS.

Of the 10 RCRA-compliant groundwater wells drilled for the remedial investigation characterization, two (299-E33-38 and -40) were in the immediate vicinity of the cribs, and log data acquired from these wells are included in this report. Both the RLS (1991) and SGLS (2001) were used to acquire data in these monitoring wells.

The RLS data collection system was not able to function properly in high-activity zones where the ^{137}Cs concentrations exceeded approximately 5,000 pCi/g. The SGLS is also incapable of measurements in the high-activity zones. A HRLS was used to collect continuous data in these zones. HRLS data are substituted for the SGLS data where appropriate.

All available data were plotted for each waste site and are included in Figures 13 through 22. Spectral gamma logging (RLS, SGLS, and HRLS) detected the gamma emitters ^{137}Cs , ^{60}Co , ^{154}Eu , and ^{125}Sb . Soil sample analytical results for the gamma emitters ^{137}Cs , ^{60}Co , and ^{125}Sb , decayed to January 2003, and total U are plotted against the spectral gamma data. RLS spectral gamma data collected in 1991 are also adjusted for decay. The soil samples were generally collected within discreet 2.5-ft intervals. For example, a sample was collected in borehole 299-E33-314 (Figure 13) between the 18.0- and 20.5-ft log depth, and it is plotted at a 19.75-ft log depth. All log and soil sample depths were converted to elevation (NAVD88) and plotted. Where comparisons can be made, there is good agreement between the soil sample analytical results and the spectral data.

One exception is uranium concentration data. Soil sample analytical results from a gamma scan reported total uranium, which includes primarily the ^{238}U and ^{235}U isotopes that represent 99.3 and 0.7 percent, respectively, of naturally occurring uranium. The SGLS and RLS detect ^{238}U indirectly by measuring $^{234\text{m}}\text{Pa}$, which is a short-lived decay product (the second daughter product) in the uranium decay series. Because of the relatively low gamma yield, this peak is not observed when only background levels of naturally occurring ^{238}U are present. When the $^{234\text{m}}\text{Pa}$ is measured by spectral gamma logging at normal 100-sec counting times, it is indicative of man-made or processed uranium contamination. The SGLS MDL for uranium using the gamma line for $^{234\text{m}}\text{Pa}$ is approximately 10 pCi/g (in the absence of other man-made radionuclides). Background for naturally occurring total uranium is approximately 2 pCi/g. In addition, where other contaminants co-exist with uranium contamination in high-activity zones, the MDL for $^{234\text{m}}\text{Pa}$ is significantly raised. Therefore, the uranium concentrations determined from soil samples acquired in high-activity zones (SGLS dead time greater than 40 percent) cannot be reliably compared with the SGLS unless the ^{238}U concentration is in excess of an MDL of approximately 300 pCi/g. Where dead time exceeds

40 percent, the HRLS is utilized. The MDL using the low-efficiency HRLS for ^{234}Pa in these high-activity zones is on the order of 10^5 pCi/g. The maximum total U concentration determined from soil samples was approximately 350 pCi/g in the high-activity zones. In low-activity zones, no man-made ^{238}U was detected in any borehole with either the SGLS or RLS. It is likely uranium exists in high-activity zones, but at levels below the detection threshold of logging equipment.

Other non-gamma-emitting radionuclides or radionuclides that emit very weak gamma rays and are not generally detectable with the SGLS that were reported in soil samples are also plotted when the radionuclide could be quantified. These radionuclides include ^{90}Sr , ^{99}Tc , $^{239/240}\text{Pu}$, and ^3H . Radionuclides for which analyses were performed and not included were barium-140 (^{140}Ba), radium-226 (^{226}Ra), beryllium-7 (^7Be), cerium (4 isotopes), cesium-134 (^{134}Cs), cobalt-58 (^{58}Co), iodine-131 (^{131}I), iron-59 (^{59}Fe), manganese-54 (^{54}Mn), plutonium-238 (^{238}Pu), plutonium-239 (^{239}Pu), potassium-40 (^{40}K), ruthenium-103 (^{103}Ru), ruthenium-106 (^{106}Ru), thorium-228 (^{228}Th), thorium-234 (^{234}Th), zinc-65 (^{65}Zn), zirconium-95 (^{95}Zr), chromium-51 (^{51}Cr), europium-155 (^{155}Eu), and thorium-232 (^{232}Th). Additionally, gross alpha and gross beta were measured. These radionuclides fell into the following categories and were not considered essential to this study: 1) concentrations were not quantified or estimated routinely, 2) radionuclide is routinely quantified but is naturally occurring (e.g., ^{226}Ra , ^{228}Th , ^{232}Th , ^{40}K), or 3) the parameter was routinely reported but was not radionuclide specific (e.g., total alpha and beta).

4.2 Major Waste Sites

Each major waste site in the study area is discussed individually in the following sections. These sites include the 216-B-43 to -50 Cribs, 216-B-57 Crib, and the 216-B-61 Crib.

4.2.1 216-B-43 Crib

Three boreholes are located within and one just east of the 216-B-43 Crib. Figure 13 shows a plot of the spectral gamma logging data and soil sample results. Three boreholes (299-E33-314, -296, and -315) were drilled into the crib in 1991. Only borehole 299-E33-296 was drilled deep enough to fully penetrate the contamination and is presumed to be representative of the area directly below the crib (DOE 1993b) and analogous to the deep vadose zone under other cribs. A high contamination zone is present between elevations of 620 and 583 ft. Within this zone the gamma emitters ^{137}Cs and ^{60}Co are measured with spectral gamma logging and total U is detected in soil samples. In addition, soil sample analytical results for non-gamma-emitting radionuclides indicate ^{90}Sr , ^{99}Tc , ^3H , and $^{239/240}\text{Pu}$. **Note: Although ^{239}Pu does emit a series of gamma lines, yields are very low, and the gamma energies are such that the lines are difficult to detect in thick casing. Hence, ^{239}Pu is not considered as a gamma emitter in this report. It was not detected in any boreholes using spectral gamma logging.** Between elevations of 583 and 535 ft, ^{137}Cs and ^{60}Co contamination are indicated; the non-gamma emitters appear to be at very low levels or non-existent. Between elevations of 520 ft and total depth of the borehole (405 ft), ^{60}Co is the dominant radionuclide and is continuously measured to total depth. Soil sample results suggest continuous ^{99}Tc from 474 ft to total depth. Total U is also identified in some soil samples at background levels (approximately 2 pCi/g) below the high contamination zone. The spectral gamma logging did not identify any man-made ^{238}U as measured by the ^{234}Pa energy peak. Soil sample results confirm the presence of ^{60}Co to near the groundwater level. Because the samples are collected ahead of the casing as it is advanced, the observed contamination is not related to “dragdown” or to movement of contaminants along the borehole casing.

Borehole 299-E33-1A, drilled in 1954, is located approximately 14 ft east of the crib. ^{60}Co contamination is exhibited at approximately the same intervals (elevation 605 ft to total depth) as in borehole 299-E33-296. The beginning of significant ^{137}Cs contamination is detected approximately 30 ft below the elevation exhibited within the crib. It is not known if other non-gamma-emitting radionuclides exist around this borehole, because no soil samples were acquired when it was drilled in 1955. The ^{60}Co concentrations are relatively higher in borehole 299-E33-1A than within the crib.

Borehole 299-E33-91 is located approximately 85 ft east of the crib. The only available data for this borehole consist of gross gamma logging conducted in 1968. The profile at that time suggested contamination existed between elevations of 570 and 483 ft (total depth) with the highest contaminated interval between 570 and 560 ft, which coincides with high ^{137}Cs concentrations in borehole 299-E33-1A. It is probable the contamination below this interval is primarily ^{60}Co that was deposited when the crib was in use. The log for this borehole is not included in Figure 13 because of its distance from the crib. It can be observed in Figure 26.

Contamination had likely entered the groundwater from this crib by 1956. In 1956, the ^{60}Co groundwater concentration in borehole 299-E33-1A was measured at 720,000 pCi/L (Figure 5). On the basis of the ^{60}Co and ^{99}Tc detected just above the current groundwater level, it is likely that contaminants continue to impact the groundwater at this location. ^{60}Co levels in the vicinity of the BY Cribs are below the drinking water standard of 100 pCi/L (Hartman et al. 2003), but there is a significant ^{99}Tc plume that appears to originate in the vicinity of the BY Cribs and extends to the north. The relatively high ^{99}Tc concentrations in the groundwater at well 299-E33-38 suggest a continuing source of contamination from the BY Cribs to the groundwater (Hartman et al. 2003).

4.2.2 216-B-44 Crib

Figure 14 shows plots of the spectral gamma logging data from boreholes associated with the 216-B-44 Crib with soil sample results, where available. Three boreholes (299-E33-316, -297, and -317) were drilled into this crib. Borehole 299-E33-02 was drilled west of the crib and 299-E33-336 northeast. Within the boundaries of the crib, a high contamination zone is present between elevations of 618 and 600 ft; the contamination was not completely penetrated by the borings. Within this zone the gamma emitters ^{137}Cs , ^{154}Eu , and ^{60}Co were measured with spectral gamma logging in borehole 299-E33-297. Soil sample results indicate total U within the high contamination zone at a maximum concentration of 100 pCi/g. Spectral gamma logging detected no man-made uranium in the vicinity; the MDL in the high contamination zone is approximately 350 pCi/g. In addition, soil sample analytical results for non-gamma-emitting radionuclides indicate ^{90}Sr , $^{239/240}\text{Pu}$, ^{99}Tc , and ^3H .

Borehole 299-E33-02 is located approximately 30 ft west of the 216-B-44 Crib. The beginning of significant ^{137}Cs contamination is detected approximately 30 ft below the elevation of contamination exhibited within the crib; ^{154}Eu is also detected in this borehole. It is not known if other non-gamma-emitting radionuclides exist around this borehole, because no soil samples were acquired. ^{60}Co contamination is detected almost continuously from an elevation of 575 ft to total depth (elevation 398 ft), and ^{137}Cs was measured intermittently to an elevation of 410 ft. It appears both ^{137}Cs and ^{60}Co reached the groundwater and may continue to impact the groundwater. Other contaminants such as ^{99}Tc may also be present.

Borehole 299-E33-336 is located approximately 61 ft northeast of the 216-B-44 Crib and approximately 90 ft southeast of the 216-B-45 Crib. ^{137}Cs contamination is detected at relatively

low levels (10 pCi/g) at the elevation of the cribs. At elevations between 560 and 570 ft, ^{137}Cs , ^{60}Co , ^{125}Sb , and ^{154}Eu are detected. The maximum ^{137}Cs concentration is approximately 800 pCi/g. Elevated concentrations of ^{137}Cs are indicated at this depth interval in borehole 299-E33-1A (216-B-43 Crib, Figure 13) and in boreholes 299-E33-03 and -22 (216-B-45 Crib, Figure 15), suggesting lateral migration of contaminants.

4.2.3 216-B-45 Crib

Three boreholes are located within the crib and one each to the south and west of the crib. Figure 15 shows a plot of the spectral gamma logging data with soil sample results where available. Three boreholes (299-E33-318, -298, and -319) were drilled into the crib. Borehole 299-E33-03 was drilled east of the crib in 1955. Borehole 299-E33-22, drilled in 1965, is located south of the crib boundary. Within the boundaries of the crib, a high contamination zone lies between elevations of 616 and 600 ft. Within this zone the gamma emitter ^{137}Cs was measured with spectral gamma logging in borehole 299-E33-298; soil sample results indicated the gamma emitters present were ^{137}Cs , total U, and ^{60}Co . In addition, soil sample analytical results for the three shallow boreholes for non-gamma-emitting radionuclides indicate ^{90}Sr , $^{239/240}\text{Pu}$, ^{99}Tc , and ^3H .

Borehole 299-E33-22 is located approximately 16 ft south of the 216-B-45 Crib. Relatively high ^{137}Cs concentrations were detected between elevations of approximately 625 and 611 ft, 8 to 10 ft higher than within the crib. This contamination may have been placed at this location from removal of contaminated soil from UPR 89 and/or the spill from the 216-BY-201 Flush Tank. A high-activity zone between elevations of 616 and 600 ft is consistent with the depth of crib contamination. A second high-activity zone beginning at an elevation of 570 ft may be significant as it relates to borehole 299-E33-03, indicating fine-grained sediments that may cause lateral spreading of contaminants. The ^{137}Cs concentrations are relatively higher and more extensive below the crib elevation than in nearby cribs. The contamination is continuous to the total depth (elevation 399.5 ft) of the borehole. Concentrations are high enough (ranging up to 10,000,000 pCi/g) such that the HRLS was used to log the majority of the borehole. In the very high gamma flux zones where the HRLS is used, the MDL for other radionuclides is greatly increased such that detection is not possible. Therefore, even though ^{154}Eu and ^{60}Co were detected in some depth intervals, these contaminants could be more extensive than presented. For example, ^{60}Co is detected only where the ^{137}Cs concentration is below 1,000 pCi/g; above this concentration level it is likely ^{60}Co is distributed continuously in the sediments as observed in other cribs. Borehole 299-E33-22 shows an influx of contamination between 1965 and 1976 such that the capability of the gross gamma instrument was exceeded (Figure 10). Current SGLS measurements indicate ^{137}Cs contamination in this interval. The only active crib at this time was the 216-B-50 Crib, which began receiving waste in 1965. Borehole 299-E33-22 is located approximately 170 ft southeast of the crib.

Borehole 299-E33-03 is located 26 ft east of the crib. ^{60}Co contamination was detected continuously from an elevation of 595 ft to the total depth of the borehole at 390 ft. ^{137}Cs was also measured between 590 and 490 ft in elevation with intermittent concentrations at low levels to the bottom of the borehole. ^{154}Eu was detected between elevations of 570 and 548 ft. The zone of higher activity beginning at an elevation of 570 ft coincides with the elevation of a zone exhibited in borehole 299-E33-22 and may indicate sediments that provide a spreading zone for contamination.

Because no soil samples were acquired, it is not known if other non-gamma-emitting radionuclides exist around this borehole. Both ^{137}Cs and ^{60}Co appear to have reached the groundwater during

initial deposition of contaminants in the crib, and ^{60}Co and some non-gamma-emitting radionuclides may continue to impact groundwater.

4.2.4 216-B-46 Crib

Three boreholes are located within the crib and two northwest of the crib. Figure 16 shows a plot of the spectral gamma logging data with soil sample results where available. Three shallow (30- to 35-ft) boreholes (299-E33-299, -310, and -311) were drilled through the crib. Boreholes 299-E33-04 and -23 were drilled in 1954 and 1965, respectively. Within the boundaries of the crib, a high contamination zone lies between elevations of 616 and 600 ft. Within this zone, the gamma emitters ^{137}Cs , ^{125}Sb , and ^{60}Co were detected by the SGLS in each borehole. Soil sample results indicated the gamma emitters present were ^{137}Cs , total U, and ^{60}Co ; ^{60}Co was detected only in borehole 299-E33-311. In addition, soil sample results for the three shallow boreholes for non-gamma-emitting radionuclides indicate ^{90}Sr , $^{239/240}\text{Pu}$, ^{99}Tc , and ^3H ; $^{239/240}\text{Pu}$, ^{99}Tc , and ^3H were not detected in borehole 299-E33-310.

Borehole 299-E33-04 and -23 are located approximately 27 ft northwest of the crib and are approximately 7 ft apart. The beginning of significant ^{137}Cs contamination is detected at an elevation of approximately 612 ft, 4 ft lower in elevation than within the crib. The ^{137}Cs contamination extends to an elevation of 540 ft in 299-E33-04 and is continuous to the total depth (elevation 400 ft) in borehole 299-E33-23. Concentrations are high enough (ranging up to 1,000,000 pCi/g) such that the HRLS was used in both boreholes. ^{60}Co contamination extends to groundwater in both boreholes at concentrations generally less than 10 pCi/g. In the very high gamma flux zones where the HRLS is used, the MDL for other radionuclides is greatly increased such that detection is not possible. Borehole 299-E33-04 is the well where high ^{137}Cs groundwater concentrations detected in 1956 led to closure of the 219-B-43 to -49 Crib.

Borehole 299-E33-23 (Figure 11) shows an influx of contamination between 1965 and 1976 similar to that in borehole 299-E33-22 near the 216-B-45 Crib. Current SGLS measurements indicate ^{137}Cs and ^{60}Co contamination in this interval. The only active crib at this time was the 216-B-50 Crib, which began receiving waste in 1965. The 216-B-50 Crib is located approximately 110 ft to the west of borehole 299-E33-23.

It is not known if other non-gamma-emitting radionuclides exist around the deep boreholes, because no soil samples were acquired below approximately 30 ft. It appears both ^{137}Cs and ^{60}Co reached the groundwater during initial deposition of contaminants in the crib, and ^{60}Co along with some non-gamma-emitting radionuclides may continue to impact groundwater. Groundwater samples collected in 1956 in borehole 299-E33-04 indicated ^{60}Co concentrations of 13,000,000 pCi/L.

4.2.5 216-B-47 Crib

Three boreholes are located within the 216-B-47 Crib. One additional borehole southwest of the crib is associated with the site. Figure 17 shows a plot of the spectral gamma logging data with soil sample results where available. Three shallow boreholes (299-E33-320, -300, and -321) were drilled through the crib to approximately 35 ft in depth (elevation of 600 ft). Within the boundaries of the crib, a high contamination zone lies between elevations of 616 and 600 ft. The full extent of contamination has not been penetrated. Within this zone, the gamma emitter ^{137}Cs was measured by the SGLS. Soil sample results indicated the only gamma emitters present were ^{137}Cs and total U

with maximum concentrations of 10,000,000 and 340 pCi/g, respectively. In addition, soil sample analytical results for the three shallow boreholes for non-gamma-emitting radionuclides indicate ^{90}Sr , $^{239/240}\text{Pu}$, and ^3H ; only borehole 299-E33-320 indicated ^{99}Tc .

Borehole 299-E33-05 is located 35 ft southwest of the crib. Significant ^{137}Cs contamination exists between the elevations of 590 and 575 ft. Other minor occurrences of ^{137}Cs exist in the borehole, most notably near the bottom of the borehole at an elevation of 410 ft. ^{60}Co contamination exists between elevations of 590 and 468 ft and is probably related to the crib. The source of the ^{60}Co contamination just above and within the groundwater is unknown. It is not continuous with the vadose zone contamination at higher elevations. It is probable these contaminants are residue left from groundwater contamination associated with the period of crib use in 1955. Because only shallow boreholes are within the crib and borehole 299-E33-05 is 35 ft from the crib, it cannot be determined if contamination entered the groundwater below this site.

4.2.6 216-B-48 Crib

Three boreholes are located within the 216-B-48 Crib. One additional borehole northwest of the crib is associated with the site. Figure 18 shows a plot of the spectral gamma logging data with soil sample results where available. Three shallow boreholes (299-E33-322, -301, and -323) were drilled through the crib to approximately 35 ft in depth. Within the boundaries of the crib, a high contamination zone lies between elevations of 616 and 600 ft. The full extent of contamination was not penetrated. No spectral gamma data are available in these boreholes. Soil sample results indicated the gamma emitters present were ^{137}Cs , total U, and ^{60}Co ; ^{60}Co was detected in only one borehole (299-E33-323). Soil sample results for non-gamma-emitting radionuclides indicate ^{90}Sr , $^{239/240}\text{Pu}$, ^{99}Tc , and ^3H . Sample results for borehole 299-E33-301 did not indicate ^{99}Tc .

Borehole 299-E33-06 is located 59 ft northwest of the crib. Significant ^{137}Cs contamination exists between the elevations of 610 and 573 ft. The beginning of the contamination is 6 ft lower in elevation than observed in the crib. Other occurrences are at 535 ft and between 418 and 400 ft in elevation. ^{60}Co contamination exists between elevations of 610 and 462 ft and is probably related to the crib. The source of the ^{60}Co and ^{137}Cs contamination just above and within the groundwater is unknown as it does not connect with the vadose zone contamination at higher elevations. It is likely these contaminants are residue left from groundwater contamination associated with the period of crib use in 1955. Because only shallow boreholes are located within the crib, it cannot be determined if contamination entered the groundwater below this site, although Fecht et al. (1977) suggested it may have entered the groundwater.

4.2.7 216-B-49 Crib

Two shallow (35-ft) and one deep (220-ft) borehole are located within the 216-B-49 Crib. Figure 19 shows a plot of the spectral gamma logging data with soil sample results where available. Within the boundaries of the crib, a high contamination zone lies between elevations of 620 and 600 ft; the full extent of contamination in the shallow boreholes may not have been penetrated. Spectral gamma data indicate ^{137}Cs , ^{125}Sb , and ^{60}Co in the boreholes. Soil sample results indicated the gamma emitters present were ^{137}Cs , ^{125}Sb , total U, and ^{60}Co . Soil sample results for non-gamma-emitting radionuclides indicate ^{90}Sr , $^{239/240}\text{Pu}$, ^{99}Tc , and ^3H , although each radionuclide was not identified in every borehole.

Borehole 299-E33-302, which was drilled to an elevation of 410 ft, shows ^{137}Cs , ^{125}Sb , and ^{60}Co extending from the bottom of the high contamination zone at an elevation of 600 ft to an elevation of 530 ft. Another zone of relatively high contamination exists between elevations of 585 and 580 ft. The vadose zone below 530 ft displays continuous ^{60}Co and intermittent ^{137}Cs to the total depth of the borehole. Soil sample results suggest continuous ^{99}Tc contamination extending below the crib to total depth. On the basis of the ^{60}Co and ^{99}Tc that have been detected just above the current groundwater level, it is probable contaminants continue to impact the groundwater at the present time.

A fourth borehole (299-E33-06), located approximately 40 ft southwest from the crib, is included in Figure 19. It is not known if the contamination exhibited in this borehole is related to the 216-B-49 Crib.

4.2.8 216-B-50 Crib

Three boreholes are located within the 216-B-50 Crib. One additional borehole northwest of the crib is associated with the site. A RCRA-compliant borehole located further northwest from the crib exhibits contamination related to this crib. Figure 20 shows a plot of the spectral gamma logging data with soil sample results where available. Three shallow boreholes (299-E33-308, -303, and -309) were drilled through the crib to approximately 35 ft in depth. Within the boundaries of the crib, a high contamination zone lies between elevations of 615 and 600 ft; the full extent of contamination in the shallow boreholes may not have been penetrated. SGLS results indicate ^{137}Cs , ^{125}Sb , ^{60}Co in the boreholes; ^{125}Sb was not identified in borehole 299-E33-308. Soil sample results indicated the gamma emitters present were ^{137}Cs , ^{125}Sb , total U, and ^{60}Co ; these radionuclides were not identified in every borehole. Soil sample results for non-gamma-emitting radionuclides indicate ^{90}Sr , $^{239/240}\text{Pu}$, ^{99}Tc , and ^3H , although each radionuclide was not identified in every borehole.

Borehole 299-E33-07 is located approximately 32 ft northwest of the crib. High ^{137}Cs concentrations were observed beginning at an elevation of 610 ft, approximately 5 ft lower in elevation than in the crib. The contamination extends to an elevation of 560 ft with ^{60}Co and ^{154}Eu also present in this interval. The remainder of the log indicates continuous ^{60}Co contamination from an elevation of 530 ft to total depth (elevation 398 ft). ^{137}Cs is intermittent between elevations of 560 and 475 ft but is continuous from 475 to 410 ft at concentrations of approximately 1 pCi/g. Borehole 299-E33-07 (Figure 9) indicated contamination in 1959 prior to the initiation of waste disposal in the 216-B-50 Crib in 1965. After the waste disposal began, contamination extended to groundwater by the 1976 log date. On the basis of the ^{60}Co that has been detected within the current groundwater level, it is likely contaminants continue to impact the groundwater.

Borehole 299-E33-40 is located approximately 160 ft northwest of the crib. This borehole indicates ^{60}Co contamination at elevations between 525 and 430 ft. It is possible that migration of contaminants to this borehole from as far away as the 216-B-49 Crib occurred during 1955. Alternatively, pre-existing contamination near the 216-B-50 Crib may have been mobilized to this location during the disposal activities that began in 1965. The log for this borehole is included in Figures 25 and 28.

The above possibilities are based on the presumption the crib was not activated until 1965 and that ITS condensate was the waste stream. However, an alternative hypothesis is that the crib received waste during the same time frame as the 216-B-43 to -50 Cribs. Data acquired from borehole

299-E33-07, located northwest of the crib, indicated contamination as early as 1959. On the basis of soil sample and logging results, the area of the crib exhibits similar contaminants and concentrations as the other cribs. The $^{137}\text{Cs}/^{90}\text{Sr}$ ratio, generally 1:1 in the 216-B-43 to -49 Cribs, is similar in this crib waste stream. The introduction of the ITS condensate waste stream in 1965 would have occurred as reported. The large volumes of fluids may have mobilized existing contamination as far away as the 216-B-45 Crib.

4.2.9 216-B-57 Crib

Four boreholes are located within the 216-B-57 Crib. Figure 21 shows a plot of the spectral gamma logging data for this crib with soil sample results where available. Two shallow boreholes (299-E33-305 and -306) were drilled through the crib to less than 50 ft in depth. Two boreholes (299-E33-24 and -304) were also drilled near or within the groundwater. A high contamination zone lies between elevations of 610 and 550 ft. The contamination is greatest in the south of the crib near the point of influent (i.e., borehole 299-E33-304). ^{137}Cs is the dominant radionuclide in the high contamination zone. On the basis of soil sample results, non-gamma-emitting contaminants exist at some depth locations. These contaminants include ^{90}Sr , ^3H , and ^{99}Tc . The contaminants exist at much lower concentrations than observed in the 216-B-43 to -50 Cribs, suggesting a different waste stream. The $^{137}\text{Cs}/^{90}\text{Sr}$ ratio, generally 1:1 in the 216-B-43 to -50 Cribs, is much different in this crib, where the ^{90}Sr concentrations are very low. ITS condensate is reported to have been disposed of in this crib. On the basis of soil sample results and geophysical surveys in the two deep boreholes, significant breakthrough to groundwater did not occur below this crib. The ^{137}Cs and ^{60}Co in borehole 299-E33-24 were probably transported by groundwater to this location from the 216-B-43 to -49 Cribs. There is some indication in borehole 299-E33-304 that ^{99}Tc could be reaching the groundwater at low concentrations (i.e., less than 1 pCi/g).

4.2.10 216-B-61 Crib

One shallow (30-ft) and two deep boreholes are located near the 216-B-61 Crib (Figure 22). This crib was never used for disposal of waste effluent. Soil samples were collected in the shallow borehole. Only ^{137}Cs contamination at the surface was detected in the boreholes. Minor occurrences of ^{137}Cs and ^{60}Co were observed in the two deep boreholes near or within the groundwater. These contaminants may have been transported to this location by groundwater contaminated from the 216-B-43 to -49 Cribs. There is no evidence that suggests this crib has been used for waste disposal.

4.3 Sphere Plots

Three-dimensional sphere plots, which are presented in Figures 23 and 24, provide an enhanced perspective of the contaminant distribution of ^{137}Cs and ^{60}Co , respectively, for all the waste sites. ^{154}Eu and ^{125}Sb were detected in only a few boreholes in the entire study area; sphere plots are not included for these radionuclides. The sphere plots show the assays recorded by the RLS (soil sample results substituted in high rate intervals where the RLS did not collect data), SGLS, and HRLS data as spheres that are colored and sized to show the position and relative concentrations of each radionuclide. All data are presented and are discussed in Section 5.0, "Interpretation of Results."

5.0 Interpretation of Results

All log data collected from the boreholes and groundwater wells in the study area were assembled and correlated in an effort to identify geophysical markers, contaminated zones, and potential contaminant sources. In addition, analytical results from soil samples collected during the BP-1 investigation (DOE 1993b) are presented with the geophysical data. Cross sections that pass through the major waste sites and connect with boreholes in the vicinity of the BY Tank Farm were constructed from spectral gamma logs collected within the study area and from spectral gamma logs collected in the BY Tank Farm between 1995 and 2002. Figure 3 shows the locations of the cross sections.

C Tech Development Corporation's Environmental Visualization System (EVS) was used to perform a geostatistical analysis of the data and to create visualizations. Visualizations generated by EVS were then selected for the report and exported to a graphics program for annotation and final presentation.

A review and comparison of historical log data with the current log data were conducted to identify any changes that may have occurred that provide insight for current interpretations.

An interpretation regarding the nature and extent of contamination for each waste site that incorporates the cross sections, visualizations, and historical data is presented. This interpretation also presents possible sources of the contamination.

5.1 Geophysical Correlation

The spectral gamma data acquired from boreholes listed in Table 4-1 were interpreted and correlated with existing geophysical and stratigraphic models for the surrounding area. A simplified stratigraphic model for the 216-B-43 to -50 Cribs was used as a starting point (Figure 4) to identify potential geophysical markers. The spectral gamma-ray logs for the naturally occurring isotopes (^{40}K , ^{238}U , and ^{232}Th) and total gamma logs for each borehole were compared and correlated with those from surrounding boreholes and checked for the presence of man-made radionuclides. After noting any influences of man-made radionuclides and changes in casing thickness on the spectral and total gamma logs, identification of geophysical markers was attempted.

Because of the heterogeneous nature of the sediments and the emplacement of double casings and grout in most deep boreholes, it was not possible to identify geophysical markers using geophysical log data. In addition, most deep boreholes exhibited contamination throughout the vadose zone, further degrading the ability to identify markers. The BP-1 remedial investigation (DOE 1993b) identified a silt layer at a log depth of 190 ft (elevation of approximately 440 ft) that was believed to be continuous under the 216-B-43 to -50 Cribs and dipping to the north at approximately one degree. This layer is interpreted as the top of the Cold Creek Unit and was considered the only possibility by DOE (1993b) for lateral contaminant migration. Log data discussed herein suggest spreading of contaminants occurred at various depths above an elevation of 440 ft.

Cross Sections A-A' (Figure 25), B-B' (Figure 26), and C-C' (Figure 27) are presented at common elevations to show the contaminant distribution and the spatial relationships between the cribs. Figure 3 shows the locations of these cross sections. Boreholes not logged as part of this characterization were included in cross sections to consider relationships of the waste sites to the

BY Tank Farm. These boreholes were 299-E33-09, 299-E33-112, and 299-E33-113, which were logged as part of the baseline characterization of tank farms between 1995 and 2000. Boreholes 299-E33-90 and -91 (digitized gross gamma logs) and 299-E33-13 (spectral gamma logging) were also included to provide control east and southeast of the 216-B-43 to -50 Crib site.

The cross sections are intended to serve multiple purposes. They were constructed such that 1) the nature and extent of contamination are portrayed at each major waste site, 2) relationships of contamination between sites (if any) are presented, and 3) probable sources of contamination and migration pathways are identified.

The contaminant profile and concentration are useful as indications of the proximity of a contamination source to the borehole. For example, occurrences of contamination at a higher elevation suggest closer proximity to a source. Higher relative concentrations also suggest closer proximity to contaminant sources.

5.2 Development of the Visualizations

Visualizations were prepared to illustrate the extent of contamination within the three-dimensional space that constitutes the vadose zone in the vicinity of the study area. Creating the visualizations required developing a geostatistical model of the ^{137}Cs and ^{60}Co contaminant distribution. Because ^{125}Sb and ^{154}Eu were detected in only a few boreholes, they were not included in the visualizations. The contaminant models are considered empirical models because they are based on data obtained by measuring the ^{137}Cs and ^{60}Co concentrations at discrete points in the subsurface and extrapolating those values into the nearby subsurface volume. They are not based on assumed waste disposal and contaminant transport mechanisms, and no effort was made to calculate hypothetical distributions using contaminant transport models.

The visualizations are intended to provide the reader with an understanding of how the gamma-emitting contaminants may be distributed in the vadose zone sediments. The visualizations can also provide an assessment of the extent to which waste process operations and waste inventory management may have contributed to contaminant distribution and to define areas of concern for subsequent investigation.

5.2.1 Development of the Interpreted Data Set

The radionuclide concentration values derived from the SGLS, HRLS, RLS, and soil sample analytical data were placed in data files that defined the position of each data point and the nuclide-specific concentration for that point. These data files were edited to create an "Interpreted Data Set" that was used to create the visualizations. The concentration data were consolidated by averaging the data points over a 5-ft interval.

The interpreted data set reflects interpretations of the nature and extent of the contamination. Specific data points may be removed from the interpreted data set if they are judged to represent contamination on the outside of the casing resulting from "dragdown" during drilling, internal casing contamination from a variety of sources, or contamination that either appears to be localized to the borehole or that may be from a remote source, such as a buried pipeline. No data points were removed from the data set.

Log run and repeat log overlaps are eliminated from the data set, and HRLS data are substituted with SGLS data where appropriate in high rate zones. For boreholes where the RLS was unable to acquire valid spectra (i.e., ^{137}Cs concentrations exceeded 5,000 pCi/g) soil sample data were substituted. The resultant concentration data are collectively referred to as the interpreted data set.

5.2.2 Three-Dimensional Visualizations

The distribution of boreholes within the study area was used to develop a three-dimensional geostatistical model. Visualizations are dependent on parameter selection as well as the subsurface data. Thus, many different visualizations are possible based on any one singular data set. The radionuclide concentration data were input to EVS subroutines that created a quadrilateral finite-element grid with kriged nodal values and the data are presented for viewing. The visualizations were constructed to include the highest and lowest node values in two-dimensional space. Nodes were established at all data sampling points, and the model does not extrapolate beyond the extent of either the assumed range value or the kriging extent. As a result, both the model and the visualizations can only extend to the maximum depth of the boreholes and the lateral extent of the geostatistical range.

The EVS software is an “expert” system that automatically determines parameter settings for the geostatistical model and for the kriging operation. These settings were used as a starting point for refinement of the model. Parameters were initially calculated by the software and then refined to create the most representative model for the ^{137}Cs distribution.

The kriging software applied an “anisotropy ratio” that allowed the user to adjust the way values are extrapolated. The anisotropy ratio applied a bias to horizontal distances over vertical distances. The program default is 10, which means that vertical distances were multiplied by a factor of 10 before the distance between the grid point and the data point was calculated. A data point 1 ft above or below the grid point will thus appear to be 10 times farther away than a data point 1 ft away at the same level. The effect is to lessen the influence of additional data points in the same borehole. The anisotropy “forces” the kriging algorithm to give more weight to data points at the same level.

Waste sites (e.g. cribs) were visualized by creating solid rectangular three-dimensional surfaces at the locations of the crib centers. The extrapolation is not affected by the insertion of the waste sites; a borehole directly across a crib still influences the node-point concentration calculation.

5.3 Comparison to Prior Gamma Logging

A comparison of the SGLS (data acquired for this report) and RLS logs (previously acquired data) was made to determine if any significant changes in subsurface contaminant profiles have occurred. The boreholes with existing RLS logs are listed in Table 4-1, and these comparisons are detailed in the Log Data Reports included in Appendix A. Discrepancies in log depth between the SGLS and RLS measurements are typical. The cause is probably depth initialization differences between the top of casing and ground level. SGLS depth measurements are consistently referenced to the top of casing. In order to compare the measurements, the RLS depths are adjusted to the more current SGLS depths based on the profiles of the respective log data. RLS data are decayed to the date of the SGLS measurements where necessary to make valid comparisons.

Apparent concentrations for the man-made radionuclides show good agreement between the logging systems when the decayed concentrations are above the SGLS MDL. Other than radioactive decay,

no significant changes in the ^{137}Cs contaminant profiles appear to have occurred in the boreholes over the time periods between log events (5 to 10 years). Because these logs were all collected well after discharges to the waste sites had ceased, the observed ^{137}Cs contaminant distribution appears to have been established during or shortly after the time the sites were in service and has largely stabilized over the intervening years.

However, the distribution of ^{60}Co in the vadose zone appears to have changed since 1992 in some boreholes in the vicinity of the 216-B-43 to -50 Cribs. Figure 28 presents comparisons of ^{60}Co concentrations between 1992 and 2002 in nine boreholes where comparisons could be made. Intervals where possible contaminant increases are observed are delineated. At elevations just above the groundwater (401 ft) contaminant increases appear in every borehole deep enough to make the comparison.

Data acquired from two RCRA-compliant groundwater wells (299-E33-38 and -40) indicate significant changes. The first logs were acquired in 1991 before the boreholes were completed as monitoring wells. Subsequent to well completion, ^{60}Co concentrations increased as shown by logs acquired in 1994 and 2002. The well completion materials (grout, bentonite, and tubing) should attenuate or mask the effects of gamma rays, thus reducing the calculated concentrations. The RCRA completion is designed to preclude downward migration along the borehole so that the increases in concentrations in these boreholes must be the result of a lateral influx of contamination.

The gross gamma logging is the best historical record of the vadose zone contamination around the waste sites. Evaluations of previous investigators are summarized in Section 3.6, "Previous Investigations." This instrumentation was designed to respond in a consistent manner over the years, making it possible to compare spatial and temporal differences in relative peak count rate. Unfortunately, the boreholes in the 200 Areas were not as consistently logged as in the tank farms. Once the limitations of these data are well understood, the data can be useful for assessing the general history of the vadose zone contamination. Data were presented as plots of the gross count rate in counts per minute (cpm) as a function of depth. These systems were effective for moderate to high activities but were not sensitive to lower radionuclide concentrations (less than about 10 pCi/g equivalent ^{137}Cs). The instrumentation became saturated in high-activity zones between approximately 10^6 - 10^7 cpm (greater than 10^8 pCi/g equivalent ^{137}Cs). Gross gamma logs were visually compared with previous data to determine, in a qualitative manner, if changes had occurred. No additional data processing or analyses were performed on these data.

When the gross gamma logs for the groundwater monitoring wells in the study area presented in Raymond and McGhan (1964), Fecht et al. (1977), and Additon et al. (1978) are interpreted based on the results of the SGLS, significant gamma-emitting contamination is observed at or below groundwater level as early as 1956. SGLS results indicate low levels of ^{60}Co and in some cases ^{137}Cs just above and below the current groundwater level. In some cases, groundwater wells in the area show little or no contamination at higher elevations in the vadose zone. The ^{137}Cs and ^{60}Co contamination that is not continuous from higher in the vadose zone and is currently near groundwater level is speculated to be the result of groundwater contamination invading the area from relatively distant sources prior to the earliest log dates (1959).

Soil samples were collected for radionuclide analysis during the BP-1 remedial investigation (DOE 1993b). In some boreholes RLS data were also collected in the same boreholes so that comparisons can be made. The boreholes were abandoned after the remedial investigation was

completed so that the SGLS and HRLS data could not be obtained. However the SGLS and RLS data are generally equivalent. Figures 13 to 22 present the geophysical log data and soil sample results for radionuclides for all the borings in the cribs. Where comparisons can be made, there is good agreement between the soil sample analytical results and the spectral data.

Note: The soil samples and RLS data represent different sample volumes and depths. The soil sample analytical results represent an average concentration over approximately a 2.5-ft depth interval and 3- to 4-in.-diameter column of soil; whereas, the geophysical data represent a larger sample volume (i.e., 12-in. sphere at each data point) and continuous sampling at 0.5- or 1-ft intervals.

5.4 Interpretation of Contamination

As noted in Section 4.0, ^{137}Cs , ^{60}Co , ^{125}Sb , and ^{154}Eu were detected in SGLS and RLS logs in the study area. After considering the relationships between the sites using the historical log data, cross sections and visualizations, it was determined the contamination conditions should be summarized and discussed in three areas: 1) the three major waste sites, 2) the relationships, if any, between the waste sites, and 3) a ^{60}Co and ^{137}Cs presence in the deep vadose zone that lies just above and within the groundwater. Visualizations of ^{137}Cs and ^{60}Co are presented in Figures 29 and 30.

5.4.1 Relationships of ^{60}Co and ^{137}Cs Contamination Between Waste Sites

Figure 25 shows a west-east cross section (A-A') originating at the 216-B-61 Crib extending near the 216-B-50, -46, and -45 Cribs and to boreholes further east of the cribs. It shows contamination extending to groundwater in the immediate vicinity of the 216-B-50, -46, and -45 Cribs; no contamination is shown near the 216-B-61 Crib. ^{60}Co contamination extends laterally from 175 ft to the northwest of the center of 216-B-50 Crib to 165 ft southeast of the 216-B-43 Crib. Borehole 299-E33-40 shows lateral migration to the northwest possibly from the nearest crib (216-B-50). Boreholes 299-E33-03, -336, and -90 also appear to indicate lateral migration of ^{137}Cs (elevation of approximately 565 ft) and ^{60}Co (elevation of 565 ft to total depth of the boreholes) to the east that probably originates from the 216-B-45 Crib.

Figure 26 shows a west-east cross section (B-B') of contamination originating at the 216-B-57 Crib extending near the 216-B-47 Crib, the 216-BY-201 Settling Tank, 216-B-43 Crib, and to boreholes east of the cribs. It shows the dominant contaminant in the 216-B-57 Crib is ^{137}Cs and that no contamination appears to have entered the groundwater from this crib. The closest borehole to the 216-B-47 Crib is 299-E33-05, located approximately 37 ft southwest. This borehole exhibits contamination attributed to the crib extending to an elevation of 468 ft, well above the current groundwater level. Borehole 299-E33-38 is located approximately 55 ft west of the 216-BY-201 Settling Tank and 70 ft southeast of the 216-B-47 Crib. The RCRA completion of this groundwater well appears to have affected the log profile so that definitive conclusions cannot be drawn regarding the source of contamination. The existence of ^{60}Co throughout much of the borehole is consistent with all cribs in the area, suggesting the source is a crib rather than the settling tank. Boreholes 299-E33-296 and -1A are within and east of the 216-B-43 Crib, 13 ft apart. The contaminant profiles suggest contamination entered the groundwater below this site. Total gamma data from 1965 for a borehole east of the 216-B-43 Crib are included in the cross section. The total counts are elevated between elevations of 570 and 485 ft and likely represent residual ^{60}Co and ^{137}Cs contamination. Borehole 299-E33-13, located 285 ft from the 216-B-43 Crib, indicates sporadic

⁶⁰Co contamination. An interval at approximately 473 ft in elevation suggests lateral movement of contaminants. It is not known if this contamination originated from the BY Tank Farm or the cribs. Between elevations of approximately 425 and 395 ft, low levels (between 0.1 and 20 pCi/g) of ¹³⁷Cs and Co are observed in boreholes drilled prior to 1991 (299-E33-1A, -05, -24, and -13). It is postulated a perched water zone may have developed from waste disposal in the BY Cribs to a maximum elevation of 425 ft, and the remnants of contamination have adhered to the casing, resulting in a “bathtub ring” in the older boreholes.

Cross Section C-C' from south-north is included as Figure 27. This cross section originates near the southwestern quadrant of tank BY-102 in the BY Tank Farm and passes through the 216-B-43, -44, -45, and -46 Cribs; there are no wells north of the 216-B-46 Crib. The profiles for each crib borehole indicate relatively high ¹³⁷Cs concentration zones 20 to 80 ft thick. ⁶⁰Co contamination is generally continuous throughout the vadose zone intercepting the groundwater. The boreholes in the tank farm are not generally deep enough to determine if tank leaks have spread north of the farm. The contamination profile of the only deep borehole (299-E33-09) in BY Tank Farm shows ⁶⁰Co contamination at an elevation of 475 ft and ¹³⁷Cs at 425 ft. These elevations and contaminants correspond with that observed in 299-E33-13 (Figure 26), which is 380 ft northeast of 299-E33-09. The concentrations for ⁶⁰Co and ¹³⁷Cs at these depth intervals are approximately 3 and 100 pCi/g and 1 and 10 pCi/g for boreholes 299-E33-09 and 299-E33-13, respectively. The source of this contamination is uncertain.

5.4.2 ⁶⁰Co and ¹³⁷Cs Contamination near Groundwater Level

Eighteen deep boreholes/groundwater wells were logged in the study area (Table 5-1 and Figure 3). Only two of these wells (299-E33-38 and -40) are considered as RCRA-compliant groundwater wells. Eleven are deep enough to intersect groundwater and could be used for water-level measurements. Three have been abandoned and two just intersect the groundwater and are not currently useful for groundwater measurements. Table 5-1 indicates the dates drilled, type of well, intervals of contamination that lie within the Cold Creek stratigraphic unit that are just above or within the groundwater, the maximum concentration measured, and comments where appropriate. Table 4-1, Section 4, includes further information for these wells and other boreholes in the study area.

Table 5-1. Groundwater Monitoring Wells Logged with the SGLS

Borehole/ Groundwater Well No.	Date Drilled	Type	Interval of Deep Contamination Below the H2/H3 Interface	Maximum Concentration (pCi/g)	Comment
299-E33-1A	Aug. 1954	Non-compliant	430-398 - ¹³⁷ Cs (intermittent) 440-396 - ⁶⁰ Co	2 22	⁶⁰ Co continuous from upper vadose zone
299-E33-296	Mar. 1992	Above groundwater	440-414 - ¹³⁷ Cs (intermittent) 440-407 - ⁶⁰ Co 440-407 - ⁹⁹ Tc	< 1 < 1 140	⁶⁰ Co continuous from upper vadose zone
299-E33-02	Nov. 1954	Non-compliant	424-409 - ¹³⁷ Cs 440-391 - ⁶⁰ Co	< 1 15	⁶⁰ Co continuous from upper vadose zone

Borehole/ Groundwater Well No.	Date Drilled	Type	Interval of Deep Contamination Below the H2/H3 Interface	Maximum Concentration (pCi/g)	Comment
299-E33-03	Nov. 1954	Non-compliant	414-411 - ¹³⁷ Cs (intermittent) 440-391 - ⁶⁰ Co	< 1 16	⁶⁰ Co continuous from upper vadose zone
299-E33-22	Aug. 1965	Non-compliant	440-399 - ¹³⁷ Cs 431-399 - ⁶⁰ Co	21,000 10	⁶⁰ Co probably and ¹³⁷ Cs continuous from upper vadose zone
299-E33-04	Dec. 1954	Non-compliant	440-400 - ⁶⁰ Co	21	⁶⁰ Co continuous from upper vadose zone
299-E33-23	Sept. 1965	Non-compliant	440-400 - ¹³⁷ Cs 440-400 - ⁶⁰ Co	9 10	⁶⁰ Co and ¹³⁷ Cs continuous from upper vadose zone
299-E33-05	June 1955	Non-compliant	426-421 - ¹³⁷ Cs 413-409 - ¹³⁷ Cs 407-396 - ⁶⁰ Co	4 2 6	⁶⁰ Co not continuous from upper vadose zone
299-E33-06	June 1955	Non-compliant	416-402 - ¹³⁷ Cs 405-390 - ⁶⁰ Co	2 3	⁶⁰ Co not continuous from upper vadose zone
299-E33-302	Jan. 1992	Abandoned	440-418 - ¹³⁷ Cs (intermittent) 440-408 - ⁶⁰ Co 440-408 - ⁹⁹ Tc	< 1 < 1 140	⁶⁰ Co continuous from upper vadose zone; ⁹⁹ Tc probably continuous
299-E33-07	Apr. 1955	Non-compliant	440-427 - ¹³⁷ Cs 419-410 - ¹³⁷ Cs 440-397 - ⁶⁰ Co	2 4 11	⁶⁰ Co continuous from upper vadose zone
299-E33-24	May 1967	Abandoned	437-410 - ¹³⁷ Cs 413-395 - ⁶⁰ Co	< 1 5	⁶⁰ Co not continuous from upper vadose zone
299-E33-304	Oct. 1991	Abandoned	435-419 - ¹³⁷ Cs (intermittent) 417-411 - ⁶⁰ Co (intermittent) 405 - ⁹⁹ Tc 405 - ³ H	< 1 < 1 < 1 < 1	⁶⁰ Co not continuous from upper vadose zone; ⁹⁹ Tc and ³ H at bottom of borehole
299-E33-25	Feb. 1969	Above GW	426, 418, 414 - ¹³⁷ Cs 410-402 - ⁶⁰ Co	< 1 < 1	⁶⁰ Co not continuous from upper vadose zone
299-E33-26	Mar. 1969	Non-compliant	431 & 409 - ¹³⁷ Cs 403-397 - ⁶⁰ Co	< 1 2	⁶⁰ Co not continuous from upper vadose zone
299-E33-38	Feb. 1991	Compliant	440-430 - ⁶⁰ Co	1	⁶⁰ Co not near groundwater

Borehole/ Groundwater Well No.	Date Drilled	Type	Interval of Deep Contamination Below the H2/H3 Interface	Maximum Concentration (pCi/g)	Comment
299-E33-40	Apr. 1991	Compliant	440-430 - ^{60}Co	< 1	^{60}Co not near groundwater
299-E33-13	Oct. 1953	Non-compliant	427-403 - ^{137}Cs 397-396 - ^{137}Cs 413-396 - ^{60}Co	18 8 8	^{60}Co not continuous from upper vadose zone

Spectral gamma logging of the non-compliant wells and abandoned boreholes indicates minor amounts of ^{60}Co (less than 20 pCi/g) and ^{137}Cs in each well (generally less than 25 pCi/g) just above and within the current groundwater level. Data acquired from borehole 299-E33-04 indicate no ^{137}Cs . The ^{60}Co contamination is continuous from the upper vadose zone to the groundwater in nine wells/boreholes. Two boreholes also show continuous ^{137}Cs contamination. The continuous nature of the contaminant profile suggests breakthrough of contaminants to groundwater occurred in the vicinity of these wells/boreholes. In boreholes where the contamination is not continuous, it is presumed breakthrough to groundwater has not occurred. These boreholes were drilled in 1954, 1955, 1967, 1969, 1991, and 1992. Data acquired from RCRA-compliant wells drilled in 1991 (i.e., 299-E33-38 and -40) do not exhibit any ^{137}Cs or ^{60}Co contamination in depth intervals near the groundwater.

The groundwater was significantly contaminated by 1956 from the BY Cribs and a perched water zone may have existed below an elevation of approximately 425 ft. ^{137}Cs and ^{60}Co contamination may have been adsorbed to rust inside the steel pipe. It is postulated that as the perched water and groundwater receded over the years, and a “bathtub ring” was formed on the inside of the casing, which resulted in apparent contamination above the current groundwater level. Therefore, the apparent contamination where it is not continuous from the upper vadose zone to the groundwater may be an artifact of an historical groundwater plume and not entirely representative of contamination distributed in the formation. The lack of contamination in the two recently drilled RCRA-compliant wells would support this hypothesis. However, these two RCRA wells have a large annular space filled with material such as bentonite and sand that impede measurement of gamma rays from the formation by the SGLS. What is presumed to be remnant ^{137}Cs exists in many boreholes in the BY Crib area at an elevation of 425 ft and below. Although it is not observed in all boreholes, 299-E33-25, -07, and -03 (Cross Section A-A’), -24, -05, -1A, and -13 (Cross Section B-B’), -09, -1A, -02, and -03 (Cross Section C-C’) indicate ^{137}Cs at this depth. This “bathtub ring” effect has been observed during geophysical logging waste site investigations at the 216-B-35 to -42 Trenches (DOE 2002a) and the 216-B-8 Crib and adjacent sites (DOE 2002b) at most deep boreholes, including 299-E33-10 and 299-E33-14 (trenches) and 299-E33-18 (near the 216-B-7A Crib), respectively. These boreholes are located approximately 1,850, 1,300, and 1,140 ft southwest, east, and southeast, respectively, from the 216-B-46 Crib. No geophysical log data have recently been collected north of the BY Cribs. It is postulated a perched water zone may have developed from waste disposal in the BY Cribs to a maximum elevation of approximately 425 ft over an extensive area in 1955.

5.5 Potential Uncertainties and Inaccuracies

The interpretations discussed above are subject to uncertainty because the number, distribution, and depth of boreholes are all limited with respect to the waste sites. Consequently, the horizontal and vertical extents of the vadose zone contamination are poorly delineated.

The construction of most boreholes is documented in the form of drilling logs. Drilling logs provide varying degrees of detail regarding the drilling operations, geologic descriptions of sediments penetrated by the drilling, radioactivity encountered during drilling, and a description of the construction configurations of the "as-built" boreholes. Geologic descriptions are subjective and the depth control can vary by as much as 5 ft. The drilling logs provide information regarding when and how the boreholes were drilled and document the occurrences of radiological contamination that were encountered during drilling.

6.0 Conclusions

Thirty-two boreholes were logged with the SGLS in the area of the 216-B-43 to -50, 216-B-57, and 216-B-61 Cribs. Gamma-emitting radionuclide concentration data were generated for naturally occurring and man-made radionuclides. Logging results were used to create a baseline data set for this collection of waste sites. Log Data Reports and log plots were prepared and published separately for each individual borehole. The Log Data Reports provide a history of boreholes and place the SGLS log data into an appropriate format to be used for waste site remediation and monitoring.

In addition, RLS log data from the BP-1 remedial investigation (DOE 1993b) were used. These data were important to the investigation because many boreholes had been abandoned in 1992 and the RLS data closely approximate the SGLS data. Soil sample results from the BP-1 investigation were also included in the data set to supplement concentrations in intervals of high gamma flux where the RLS could not collect usable data. Soil sample results of non-gamma-emitting radionuclides were plotted with the RLS and SGLS data to provide a complete snapshot of contamination in the cribs.

Empirical ^{137}Cs and ^{60}Co contamination distribution models were created. These cross sections and models were used to create visualizations of the contamination distribution that were discussed in this report. Data collected between 1995 and 1999 for the tank farms baseline characterization of BY Farm were incorporated with the current characterization data to evaluate the relationships of contamination. A review of historical information was conducted to integrate with current information when interpreting the data. The information relating to the contamination distribution beneath the study area can be used to locate additional characterization boreholes, implement a monitoring program, to provide input for risk assessment calculations, and for planning site remediation activities.

The gamma-emitting radionuclides ^{137}Cs , ^{60}Co , ^{125}Sb , and ^{154}Eu were detected while logging in this study area. In addition to these radionuclides, total U was also detected in soil samples. The major waste sites (216-B-43 to -50 Cribs, 216-B-57 Crib, and the 216-B-61 Crib) contained sufficient boreholes such that an evaluation could be made. Each site except for the 216-B-61 Crib exhibited ^{137}Cs as a significant contaminant, with the highest concentration measuring about 10^7 pCi/g south of

the 216-B-45 Crib. ^{60}Co contamination is pervasive laterally in the vadose zone and reaches the groundwater below the 216-B-43 to -50 Cribs. Historical log information collected after 1959 suggested the possibility of contaminant breakthrough to the groundwater in the vicinity of all the 216-B-43 to -50 Cribs. However, 216-B-47 and -48 Cribs did not have deep boreholes to groundwater close to the cribs such that an evaluation could be made. No evidence of breakthrough to the groundwater at the 216-B-57 and -61 Cribs was indicated.

Soil sample results show non-gamma-emitting radionuclides exist in the high concentration zones just below each crib, at elevations between 616 and 600 ft. These radionuclides include ^{90}Sr , ^{99}Tc , $^{239/240}\text{Pu}$, and ^3H . In two deep boreholes where soil samples were collected, ^{99}Tc is measured near the top of the groundwater and appears to have followed the same pathway in the vadose zone as ^{60}Co . On the basis of all the data reviewed, ^{60}Co and ^{99}Tc may continue to impact the groundwater underlying the cribs. Radionuclide contamination currently shown to exist in groundwater includes ^{99}Tc , ^{60}Co , and uranium (Hartman et al. 2003). Uranium is not detected in the vadose zone by any spectral gamma logging, and soil samples show total uranium above background concentrations only in the high concentration zones just below the cribs. In these high-activity zones the MDL for uranium using spectral gamma measurements is greatly increased and may not be detected at the maximum concentrations detected with soil samples (i.e., 350 pCi/g). There is no evidence of vadose zone uranium contamination near the groundwater. A more credible source for the uranium contamination in groundwater is the vadose zone plume originating near tank BX-102 in the BX Tank Farm. This vadose zone contamination extends downward and intercepts groundwater east-northeast of the BX Tank Farm. This contamination is discussed in greater detail in the *216-B-8 Crib and Adjacent Sites Waste Site Summary Report* (DOE 2002b).

The 216-B-50 Crib is reported as not having been used until 1965, at which time ITS waste was disposed of in the crib. However, contamination was observed in a borehole northwest of the crib as early as 1959. Logging and soil sample results of recent investigations suggest the contaminants in the crib are very similar to that observed in the 216-B-43 to -49 Cribs. The similarities include radiological constituent, concentrations of constituents, ratios between constituents, and depths of deposition. The contamination, according to log and soil sample data, is not consistent with the ITS waste that was disposed of in the 216-B-57 Crib. It appears this crib was utilized at the time the adjacent 216-B-43 to -49 cribs received waste in 1955.

There is evidence of extensive lateral migration of contaminants in the vicinity of the BY Cribs. The full extent of contamination cannot be determined because of the relatively sparse distribution of boreholes, but contamination is observed over a distance of 600 ft between boreholes 299-E33-40 and -13. Boreholes in the vicinity of the 216-B-57 and -61 Cribs suggest no influence or commingling of contaminants from the 216-B-43 to -50 Cribs. There is no borehole control immediately to the north of the cribs, and because the BY Tank Farm boreholes are not deep enough, it cannot be determined if crib contamination extends southward or tank farm contamination extends northward to commingle with crib contamination. On the basis of the one degree north stratigraphic dip in the area (DOE 1993b), the BY Tank Farm contamination would be expected to invade the area of the cribs. Borehole 299-E33-13, southeast of the cribs and northeast of the tank farm, exhibits residual contamination at an elevation of 475 ft. It cannot be determined if this contamination originated from the farm, the cribs, or both.

^{137}Cs and ^{60}Co contamination were detected in all deep boreholes drilled in the 1950s at a depth consistent with historical and current water levels. Boreholes drilled to the groundwater in the area

since the 1990s did not exhibit any contamination. Although this lack of contamination may be related to differences in well construction, the contamination is postulated to be derived from groundwater contamination present in the 1950s. The contamination observed by the SGLS may have been adsorbed by rust and scale inside the casing and does not represent formation contamination. The source of the historical $^{60}\text{Co}/^{137}\text{Cs}$ contamination is most likely the 216-B-43 to -50 Cribs. Data visualizations suggest that the BY Tank Farm may also be a potential source of the contamination. ^{137}Cs and ^{60}Co contamination entered the groundwater in 1955 from the 216-B-43 to -50 Cribs (Thomas et al. 1956). Current log data show a continuous record of these contaminants to the current groundwater level. Many boreholes in the vicinity and in boreholes more than 1,000 ft away in the southeast and southwest also exhibit these contaminants (i.e., ^{137}Cs and ^{60}Co) near the groundwater/vadose zone interface even though there is no continuous record of vadose zone contamination from the high concentration zones to the deep vadose zone. This residual contamination is probably the result of groundwater contamination from sources such as the BY Cribs that may have impacted the groundwater as early as 1955. It is postulated that a perched water zone was created during disposal to the cribs that may have extended to an elevation of 425 ft, approximately 24 ft higher than the current groundwater level.

A comparison of historical gross gamma logs and current SGLS logs, as well as, a more direct comparison of more recent RLS spectral logs with the SGLS, suggest ^{137}Cs contamination profiles and concentrations at the waste sites are relatively stable over time. There is some indication migration of ^{60}Co contamination continued to occur at least between 1992 and 2001. This migration does not appear to be along laterally continuous lithologic control and occurs at varying depth intervals from borehole to borehole. Changes in the ^{60}Co profile just above the groundwater (elevations between 408 and 401) are noticeable in boreholes where comparisons can be made.

Another site in the area that contained waste is the 216-BY-201 Catch Tank. Although there has been a release associated with this site, limited cleanup occurred in the top few feet of the site and the site is not believed to have impacted the deep vadose zone. However, there are no boreholes in close proximity and the impact of this site cannot be completely evaluated.

Geophysical interpretations of the stratigraphic relationships between boreholes could not be made using spectral gamma logging. The double casing and grout in most boreholes preclude accurate measurement of the naturally occurring radionuclides (^{40}K , ^{238}U , and ^{232}Th). Increases in the ^{40}K concentration can be used to define the contact between the Hanford H1 and H2 units that may represent a potential spreading surface for contaminants and can be used to predict the direction of lateral migration in the vadose zone. The elevation is approximately 600 ft in the area of the cribs. The contact between the Hanford H2 and the Cold Creek Unit appears at approximately 440 ft in elevation. The base of the H2 is defined where a silty facies is encountered as described in DOE (1993b) and Wood et al. (2000). This silt layer is believed to be continuous beneath the 216-B-43 to -50 Cribs and dipping one degree to the north.

7.0 Recommendations

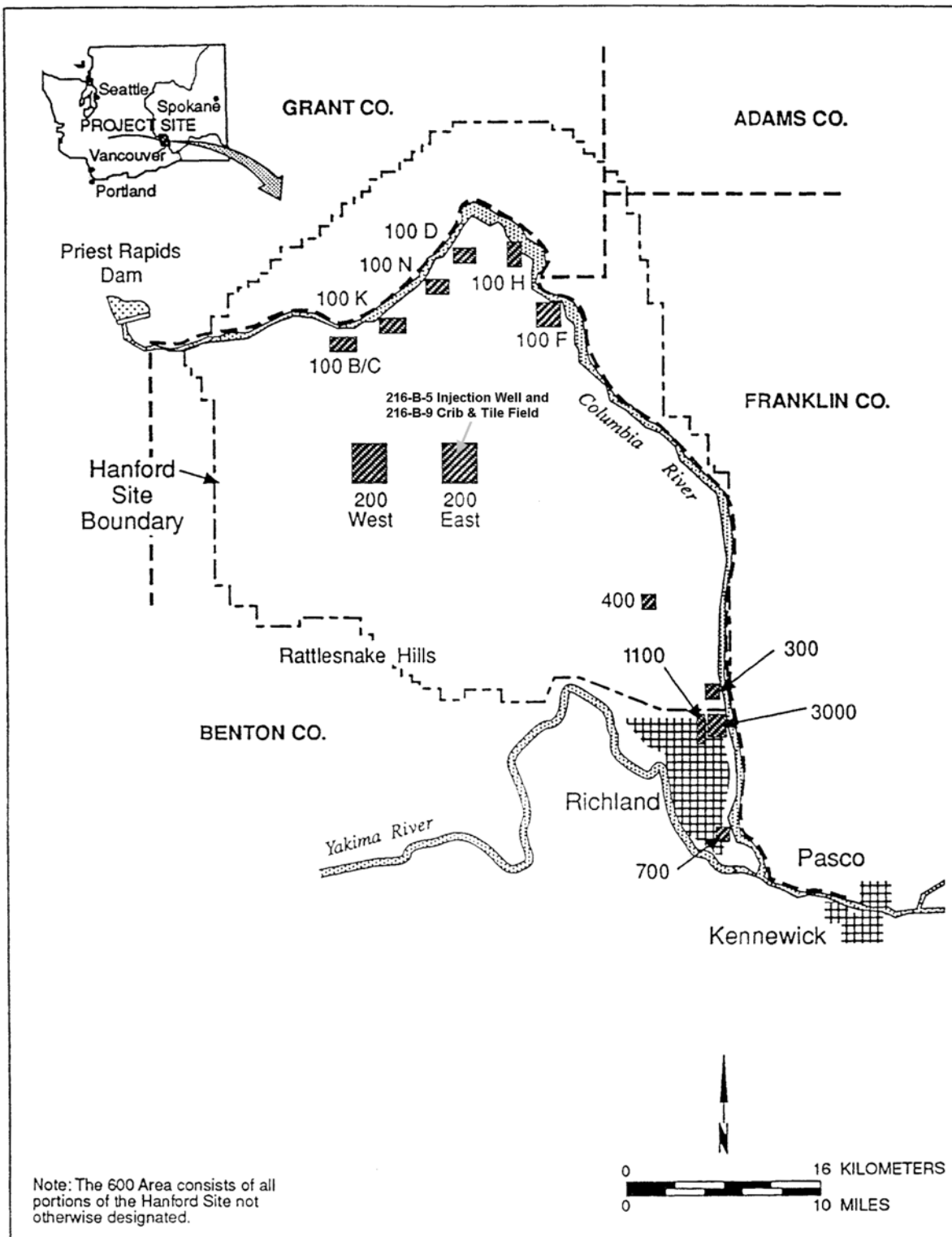
The vadose zone characterization of the study area was conducted to establish a baseline value for gamma radionuclide activities in vadose zone sediments surrounding the waste sites. This baseline can be used to compare with future logging data to determine if changes have occurred and to assess the rate and potential causes of the changes. The data from this characterization project can also be correlated and compared with information other than concentration data, such as moisture data.

Characterization within the study area has identified several areas where future characterization efforts should be conducted. The 216-B-43 to -50, -57, and -61 Cribs are reasonably well characterized, although the lateral extent of contamination is poorly defined. Relationships between waste from the BY Tank Farm and the cribs are not defined with the existing boreholes. The possibility that ^{60}Co and ^{99}Tc co-exist in the vadose zone or at least travel through the vadose zone in similar pathways should be explored. ^{60}Co is a gamma-emitting contaminant that is pervasive in the BY Tank Farm and in the cribs and is easily detected using spectral gamma logging. If a relationship exists between ^{60}Co and ^{99}Tc , a reasonable contaminant inventory for the higher risk ^{99}Tc could be established. A borehole is recommended to be drilled north of the BY Tank Farm (between the farm and the BY Cribs) to groundwater to assess the deep vadose zone and to determine the relationships of the BY Farm and BY Crib contamination so that potential sources can be evaluated. Moisture measurements should be made to detect any variations in moisture content and to locate zones of high moisture content that may facilitate $^{60}\text{Co}/^{99}\text{Tc}$ migration. Soil samples should be obtained from the vadose zone to determine if non-gamma-emitting radionuclides are present and the relationship of ^{60}Co to ^{99}Tc should be evaluated. In addition, the vadose zone/groundwater interface should be sampled to provide confirmation as to whether the occurrences of ^{137}Cs and ^{60}Co in older groundwater wells are distributed in the formation or are adsorbed to the inside of the casings. Boreholes should be drilled in all cardinal directions from the 216-B-43 to -50 Cribs to determine the lateral extent of contamination.

Any new boreholes and existing boreholes that are related to the area of contamination should be placed in a monitoring program to measure contaminant movement. Selected boreholes in the BY Tank Farm are currently being monitored with the Radionuclide Assessment System. This system is less complicated than the SGLS and provides data suitable for monitoring purposes, and it should be used in selected boreholes to track migration of the ^{60}Co contamination.

Figures

The following section presents the figures for this report in the order in which they were cited.



modified from DOE (1993b)

Figure 1. Hanford Site and Area Designations

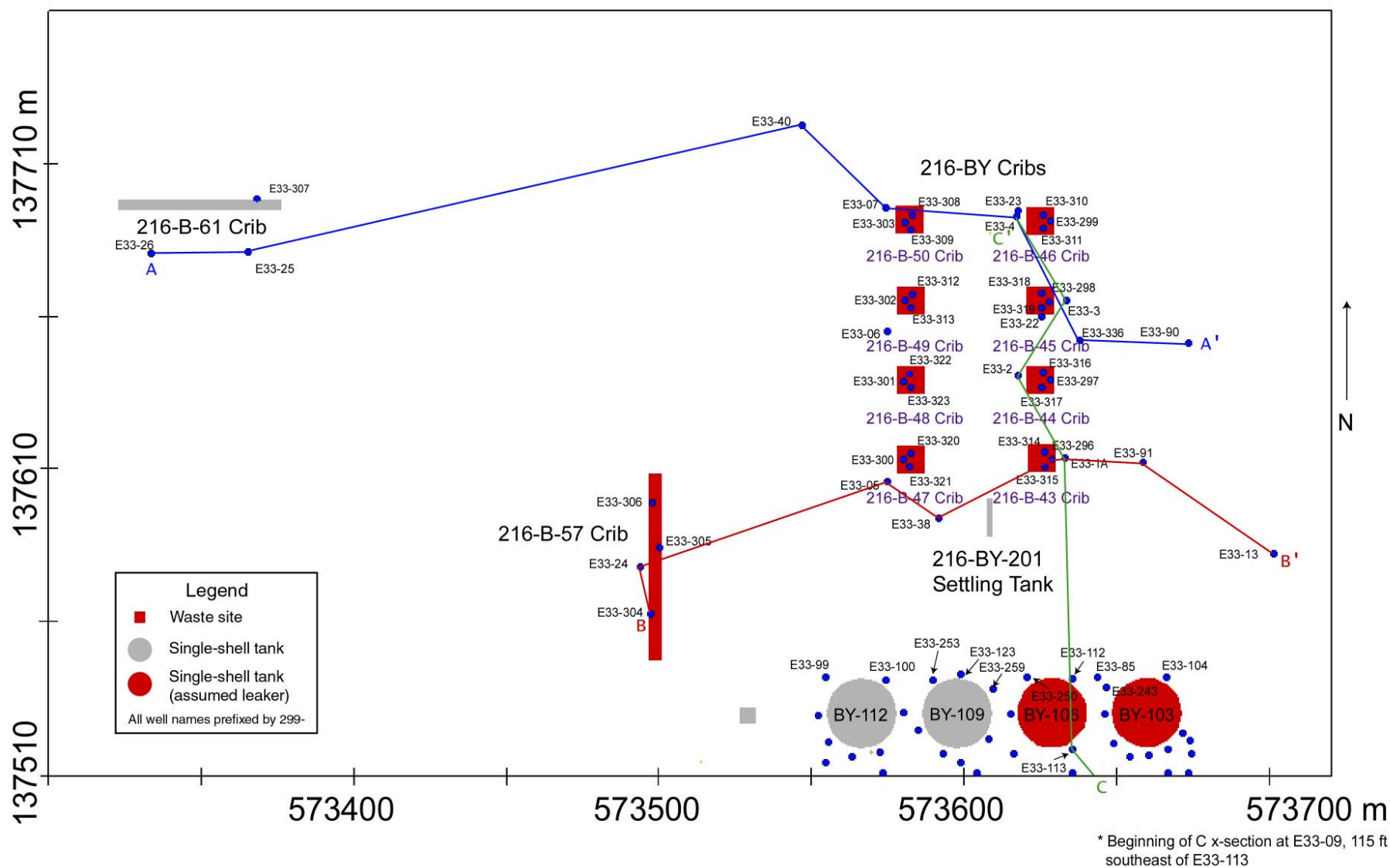
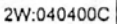


Figure 3. Map of the 216-B-43 to -50, -57, and -61 Crib, and Adjacent Waste Sites and Boreholes



from DOE (2000a)

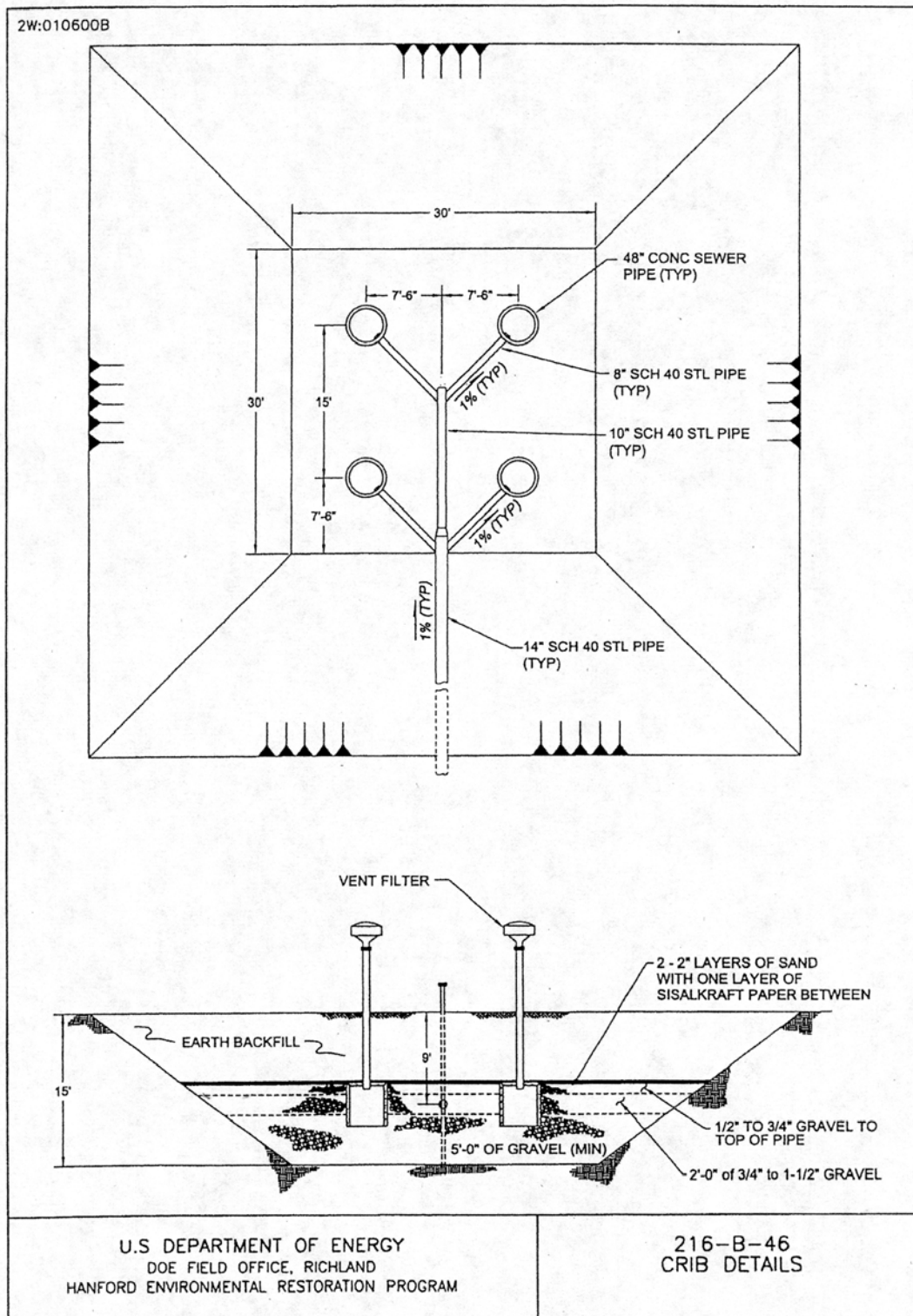
Figure 4. General Stratigraphy in the Vicinity of the BY Cribs



Figure 6a. View of the 216-B-43 through -50 Cribs from the Southwest

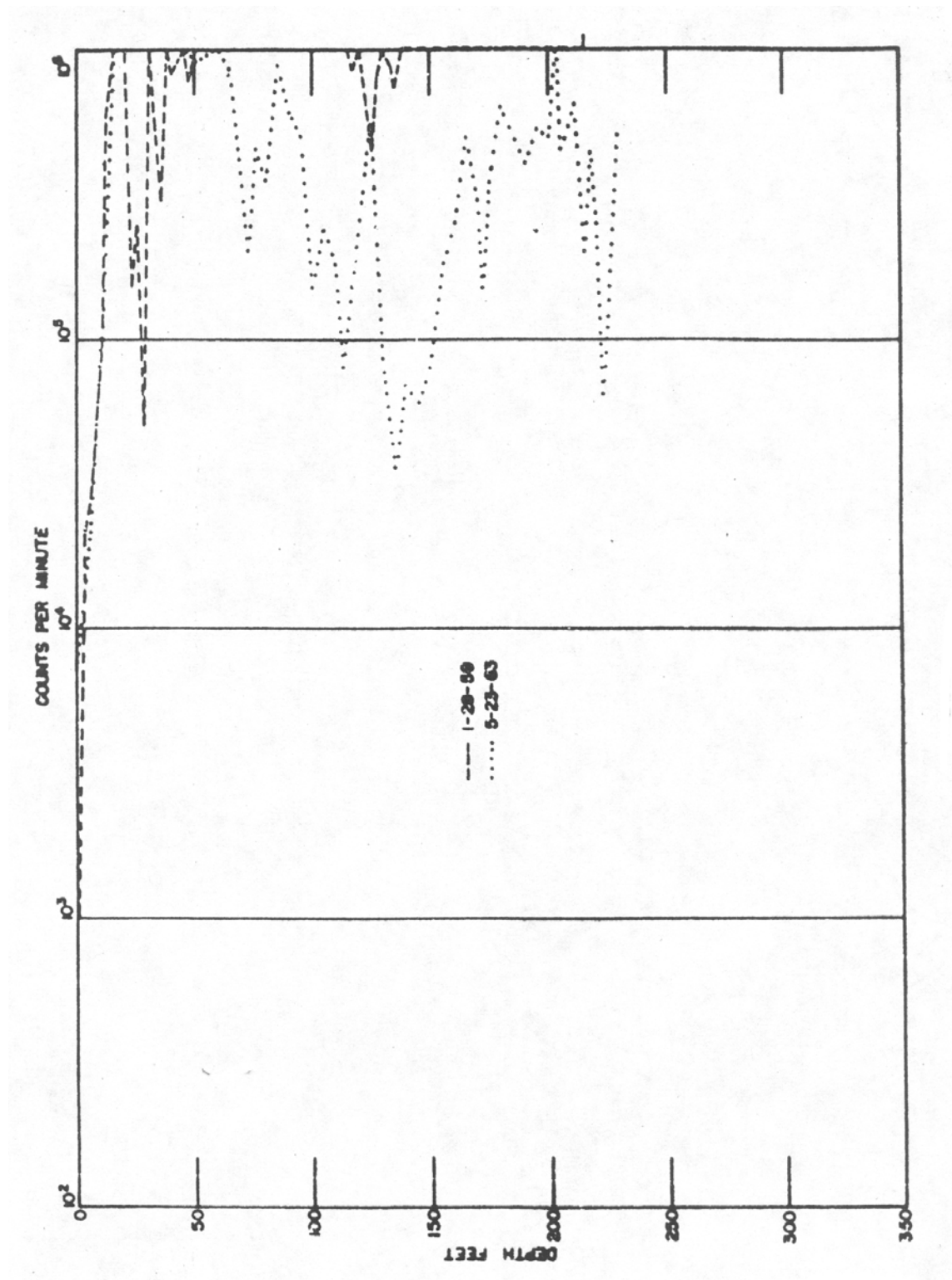


Figure 6b. View of the 216-B-43 through -50 Cribs from the Southeast



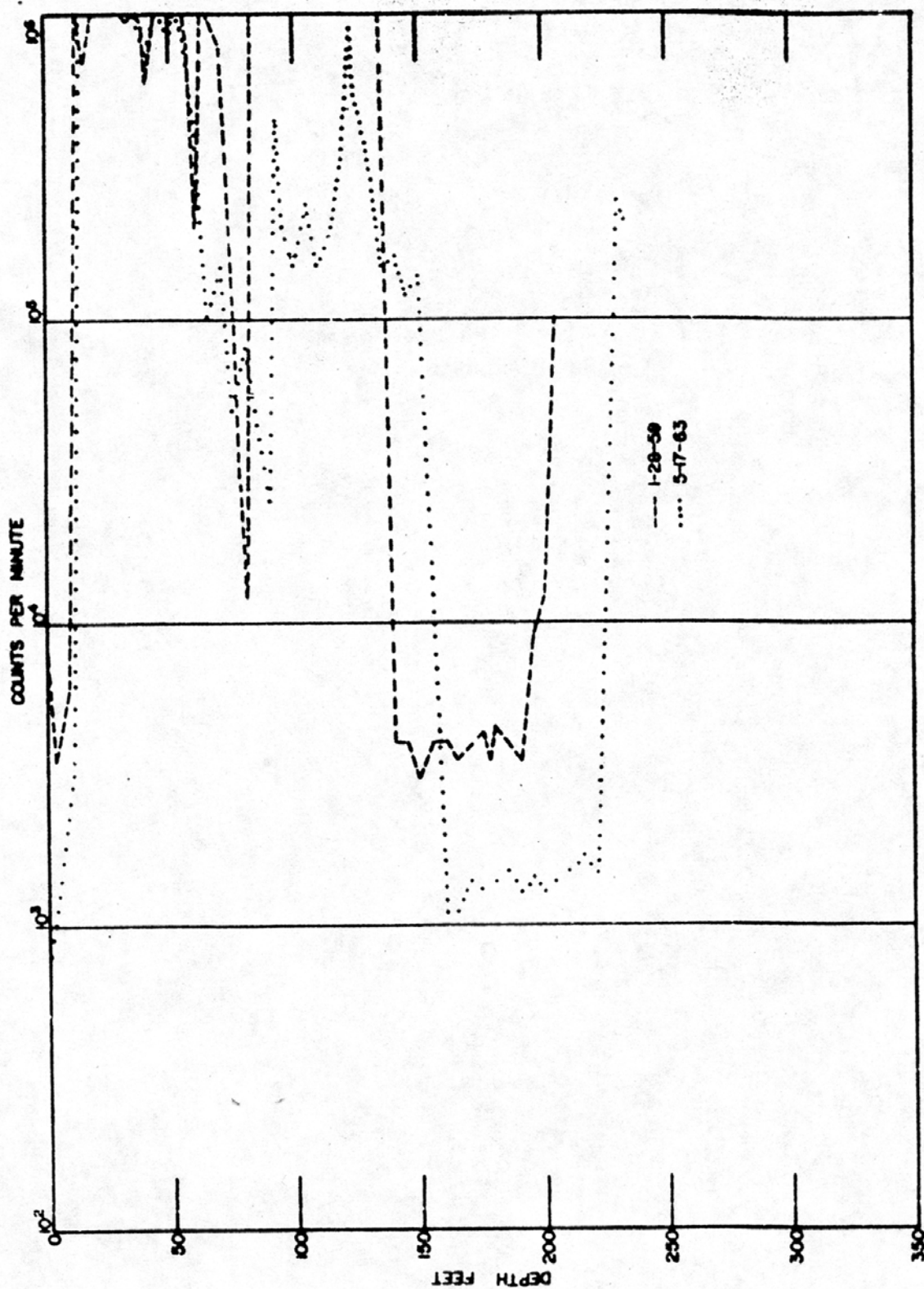
from DOE (2000a)

Figure 7. Construction Diagram for the 216-B-46 Crib



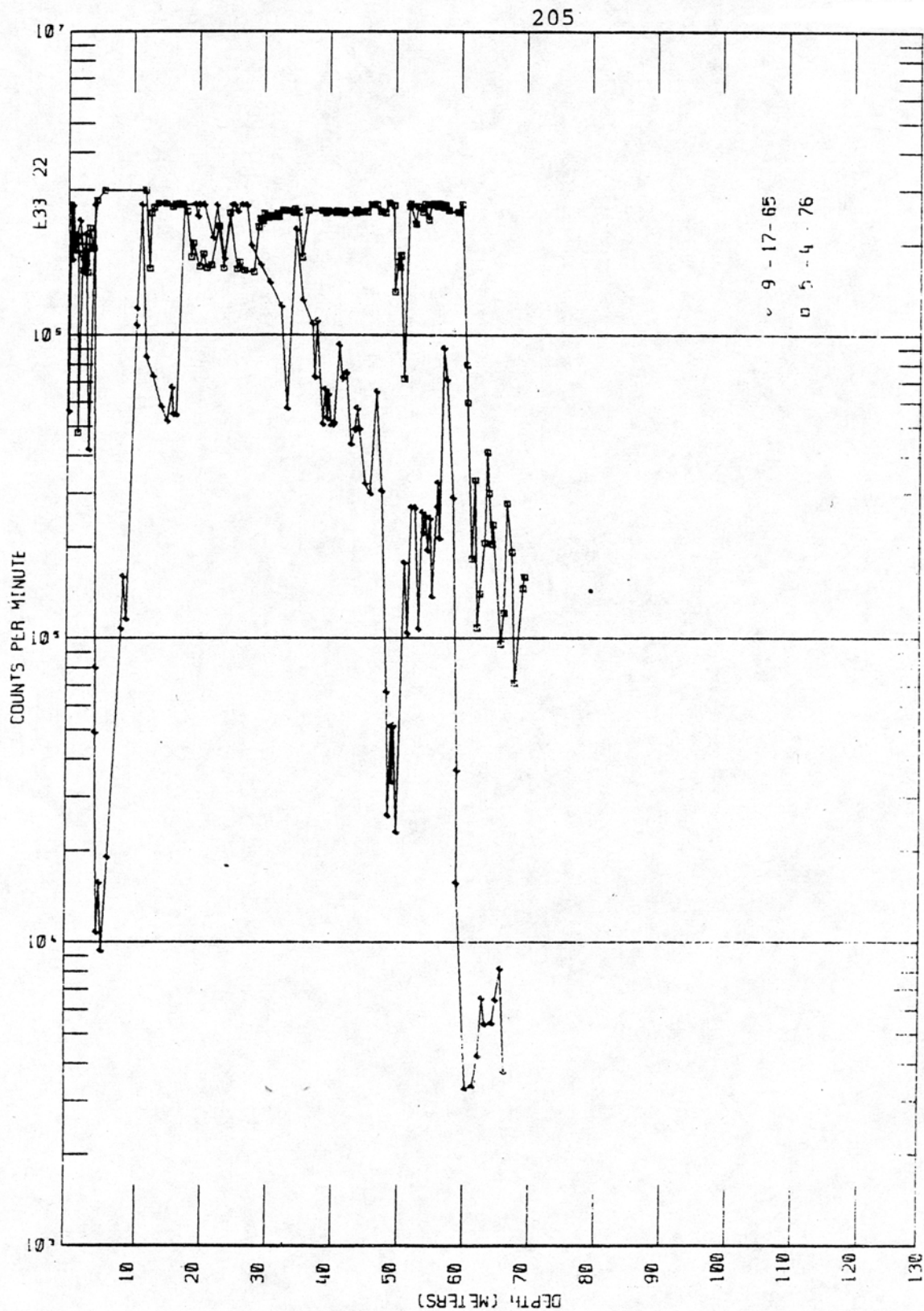
from Raymond and McGhan (1964)

Figure 8. Well 299-E33-4 Scintillation Log



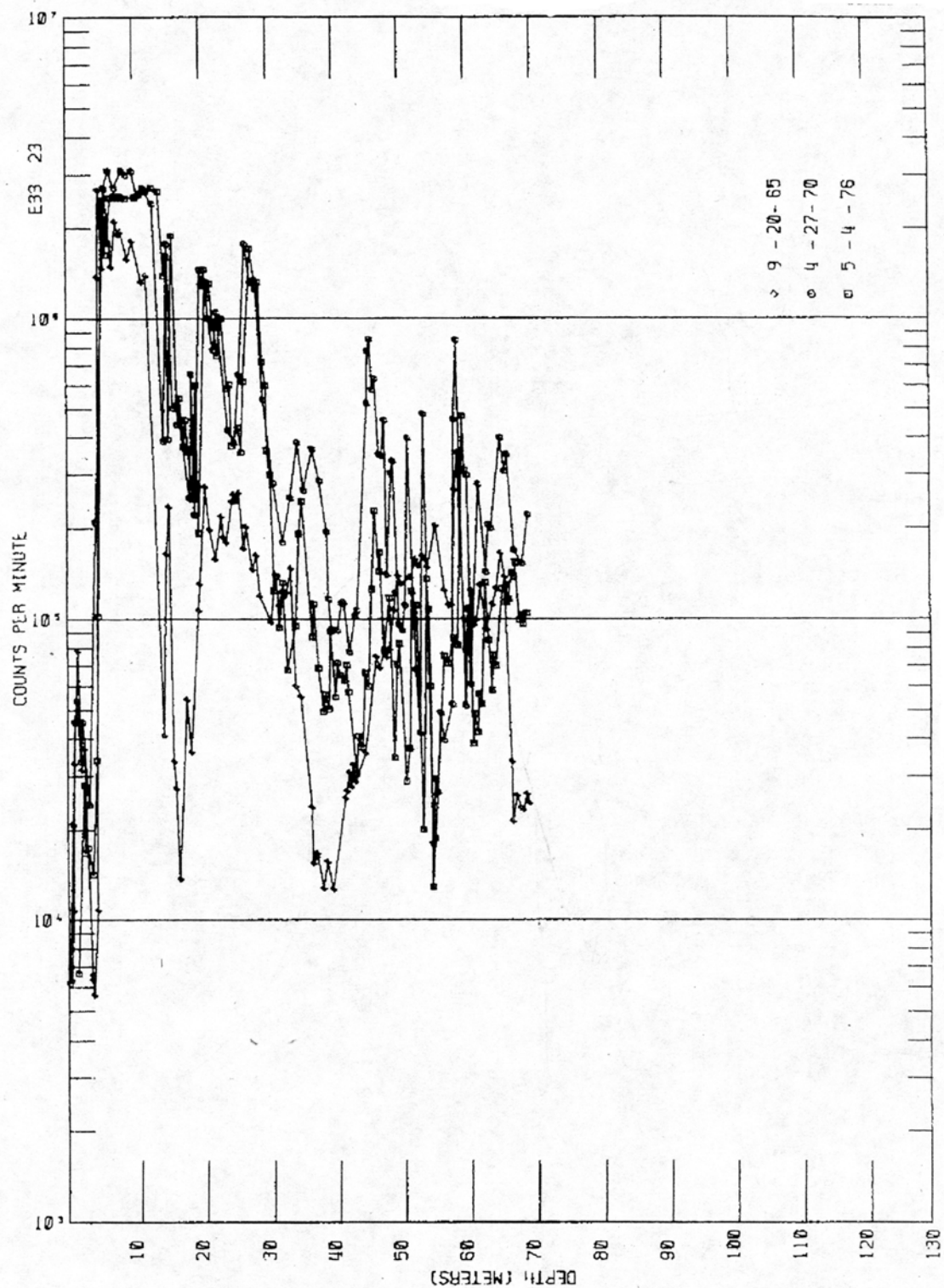
from Raymond and McGhan (1964)

Figure 9. Well 299-E33-7 Scintillation Log



from Fecht et al. (1977)

Figure 10. Well 299-E33-22 Scintillation Log



from Fecht et al. (1977)

Figure 11. Well 299-E33-23 Scintillation Log

216-B-43 Crib

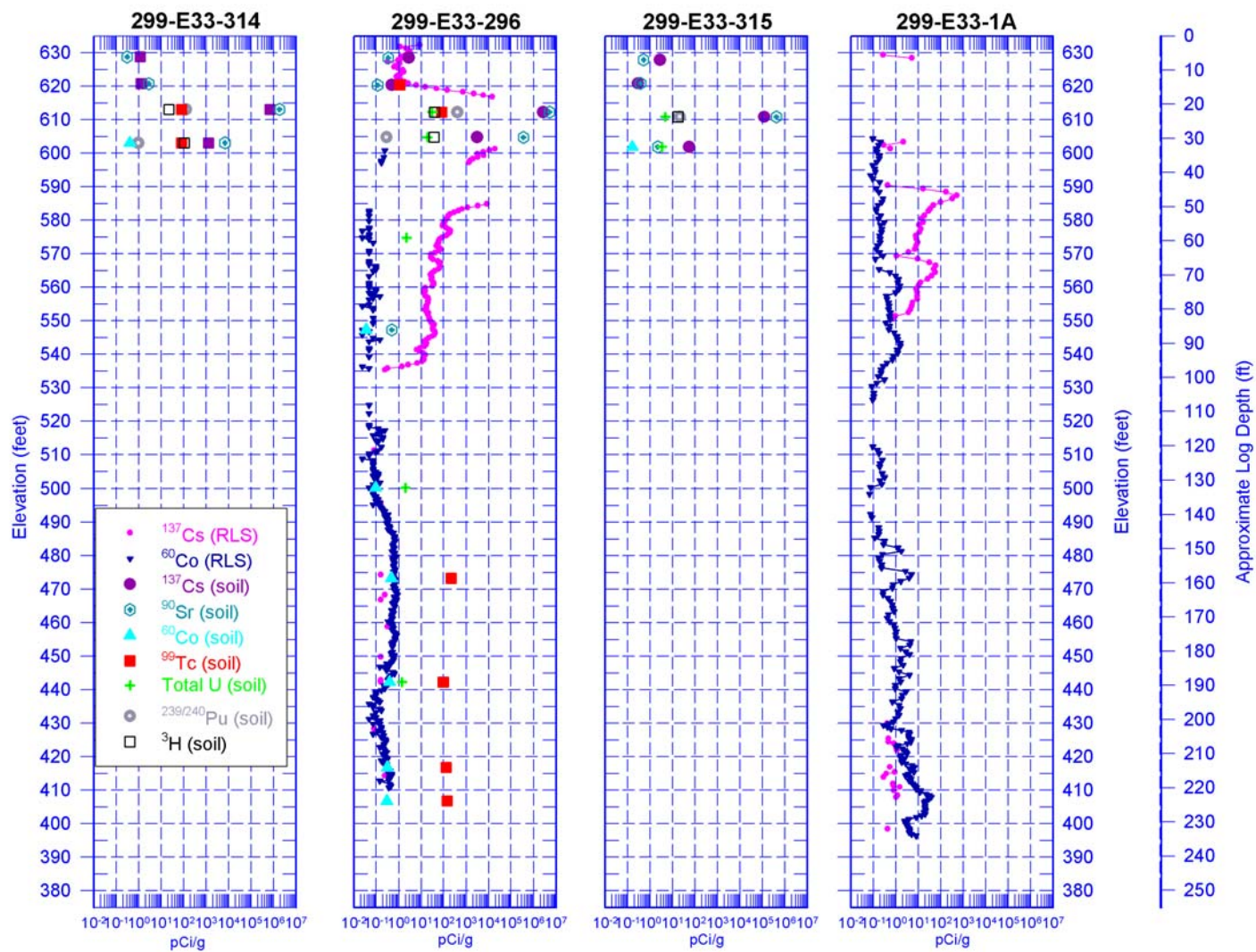


Figure 13. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-43 Crib

216-B-44 Crib

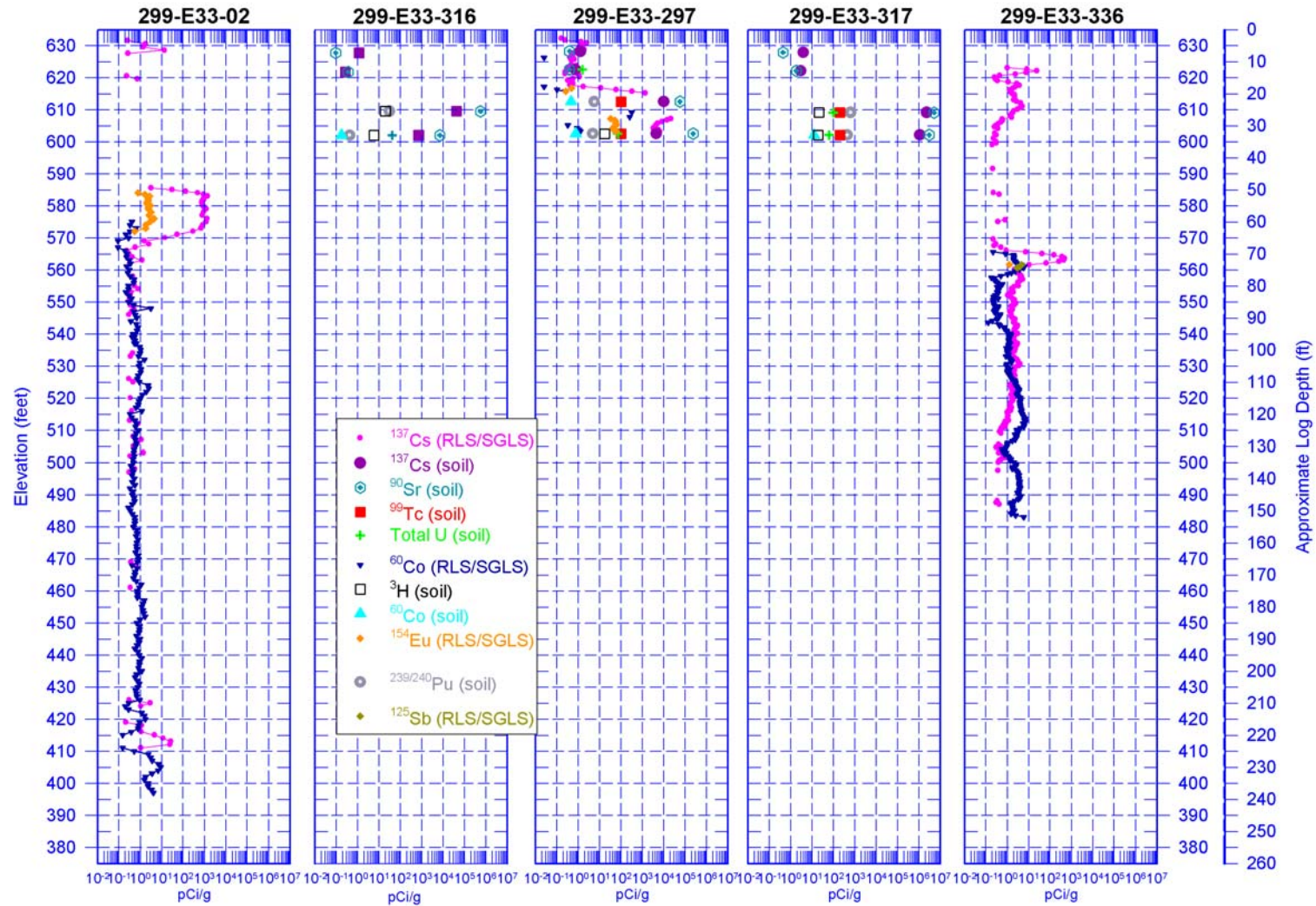


Figure 14. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-44 Crib

216-B-45 Crib

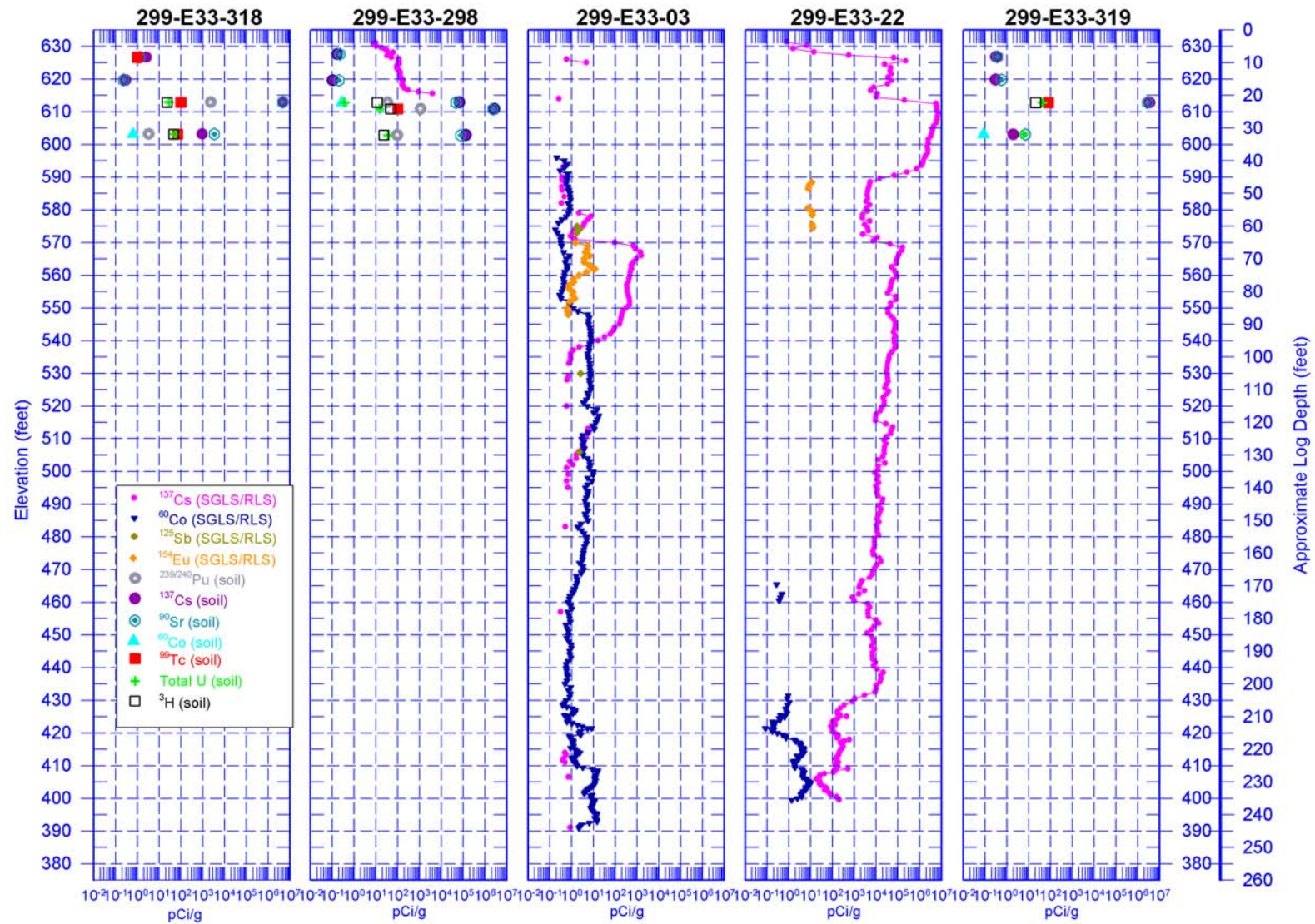


Figure 15. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-45 Crib

216-B-46 Crib

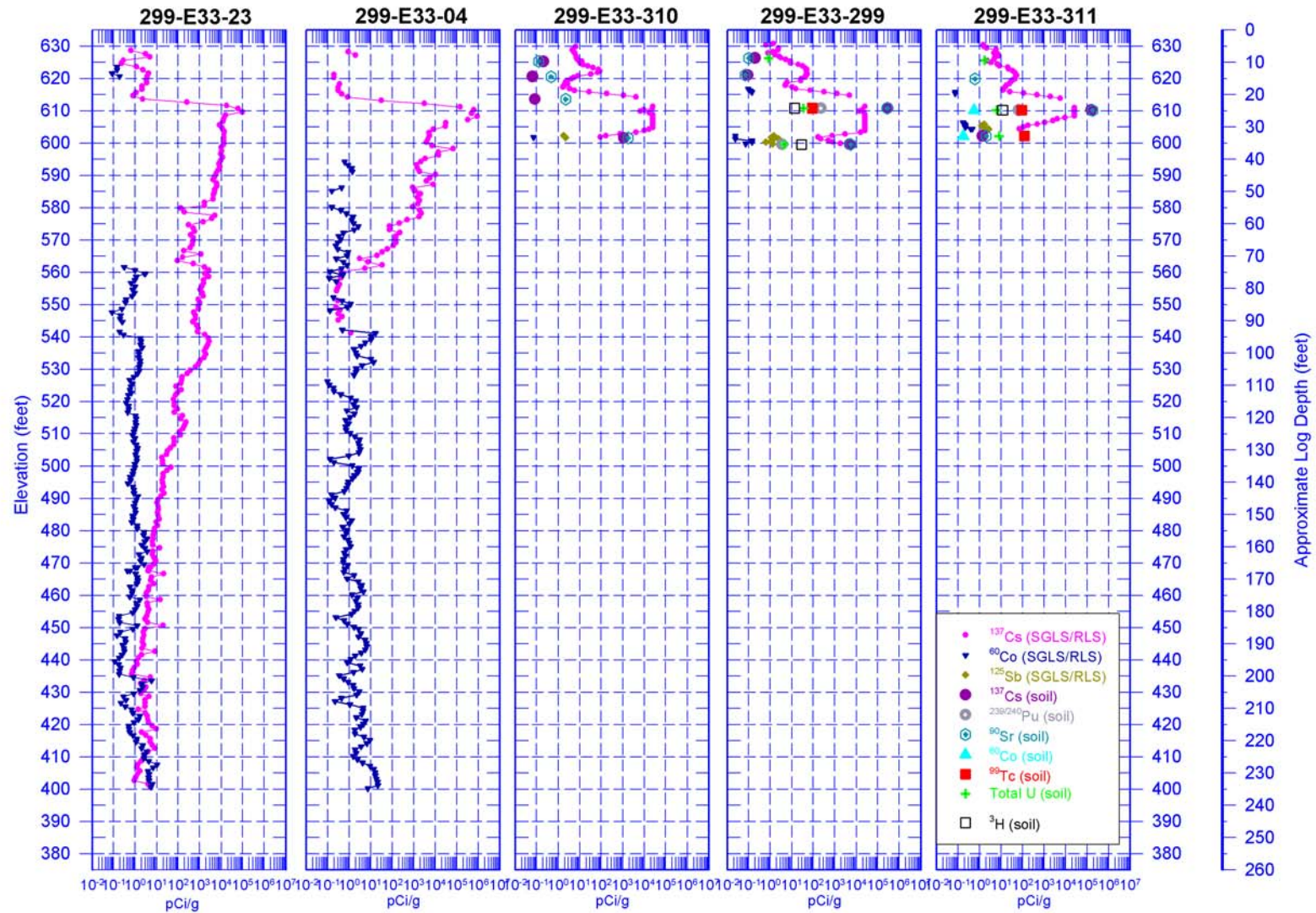


Figure 16. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-46 Crib

216-B-47 Crib

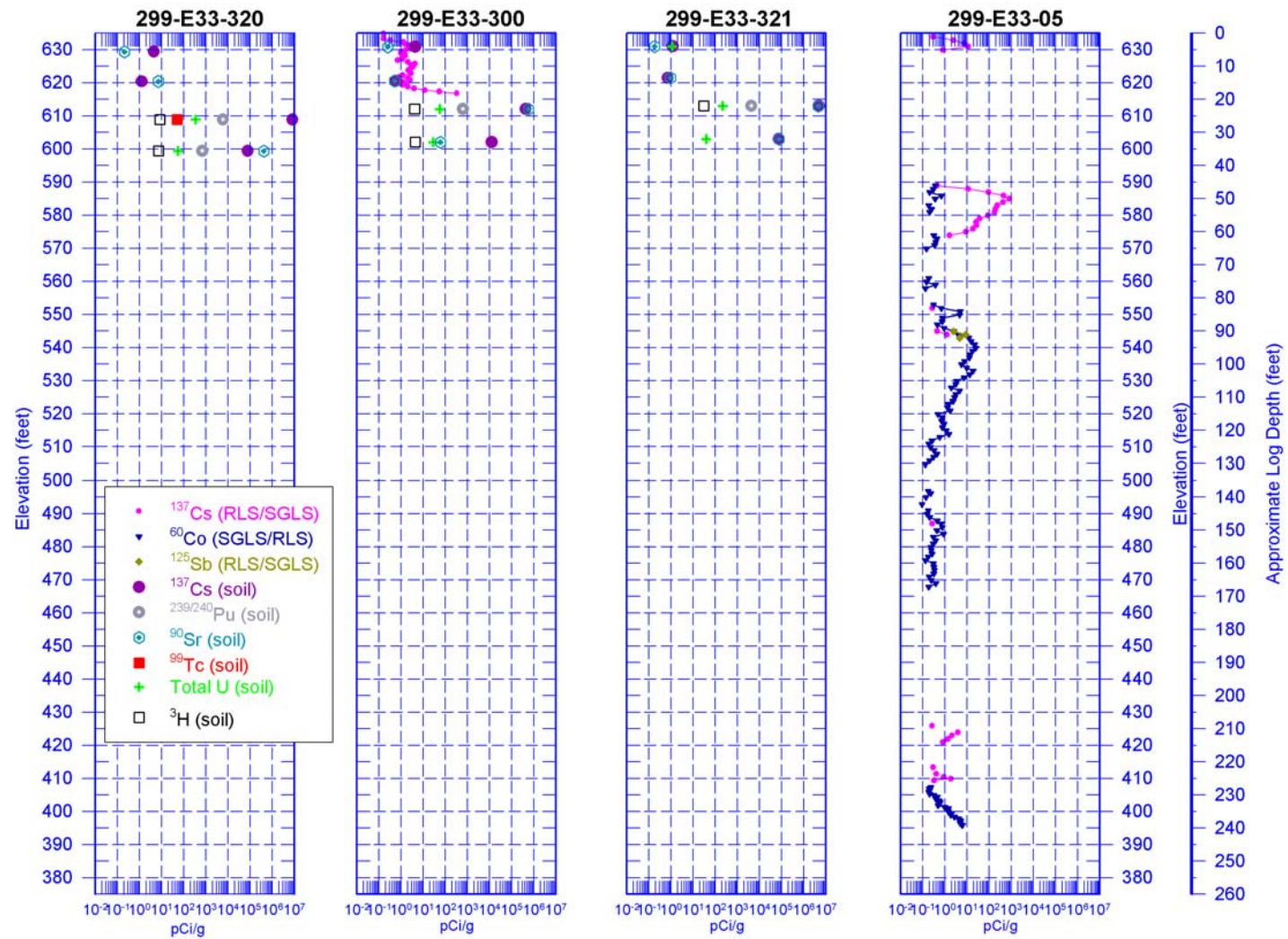


Figure 17. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-47 Crib

216-B-48 Crib

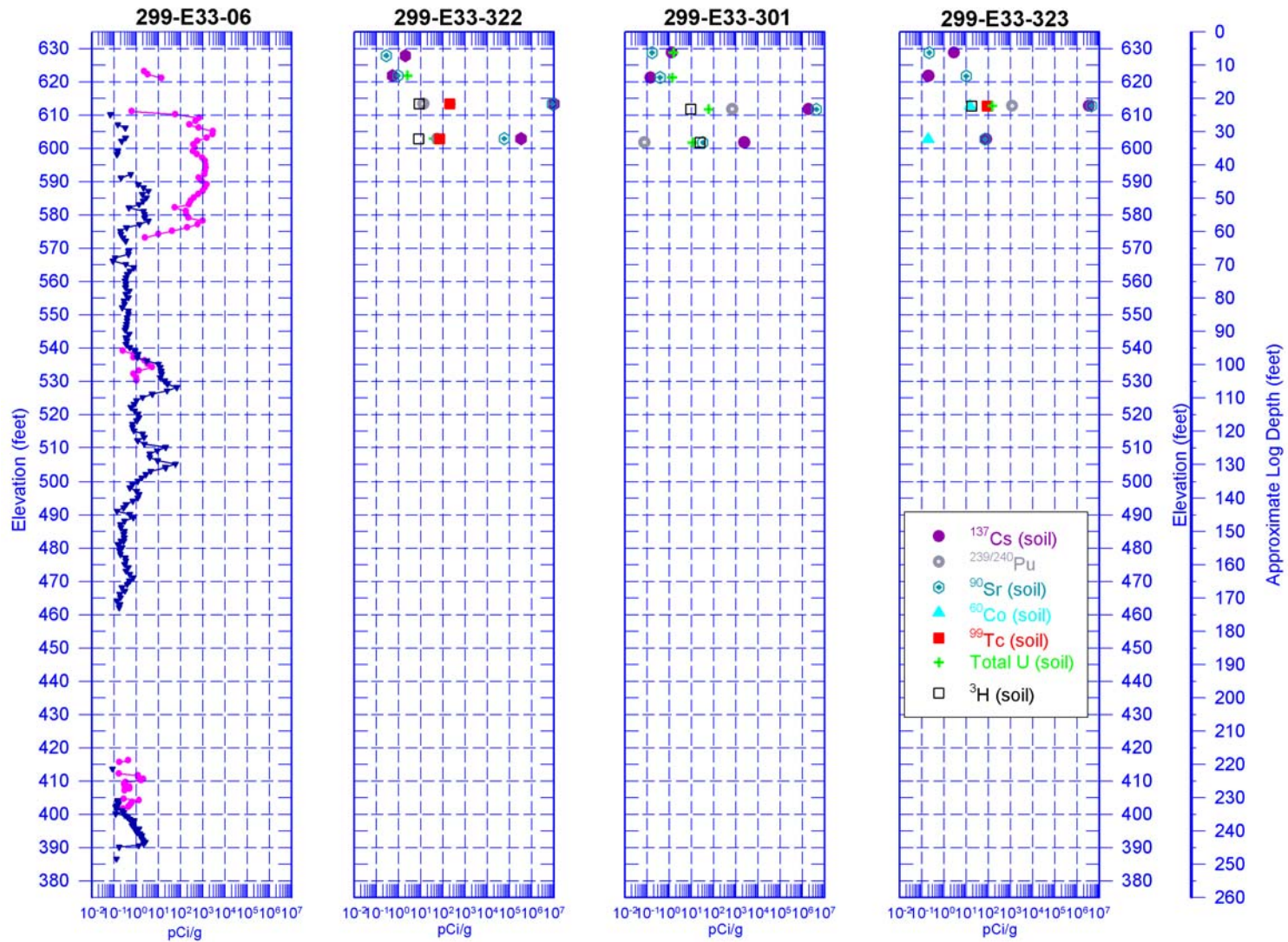


Figure 18. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-48 Crib

216-B-49 Crib

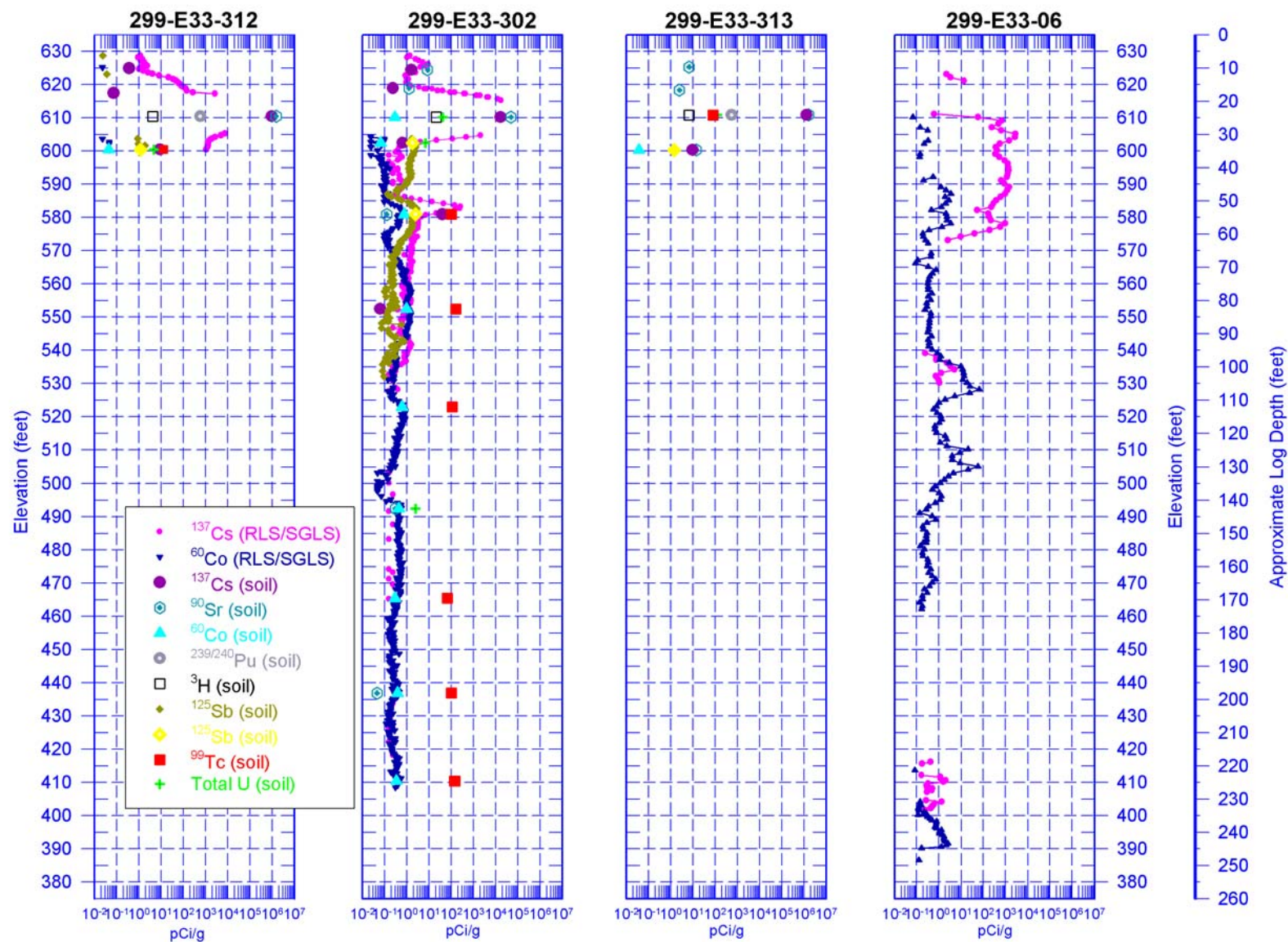


Figure 19. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-49 Crib

216-B-50 Crib

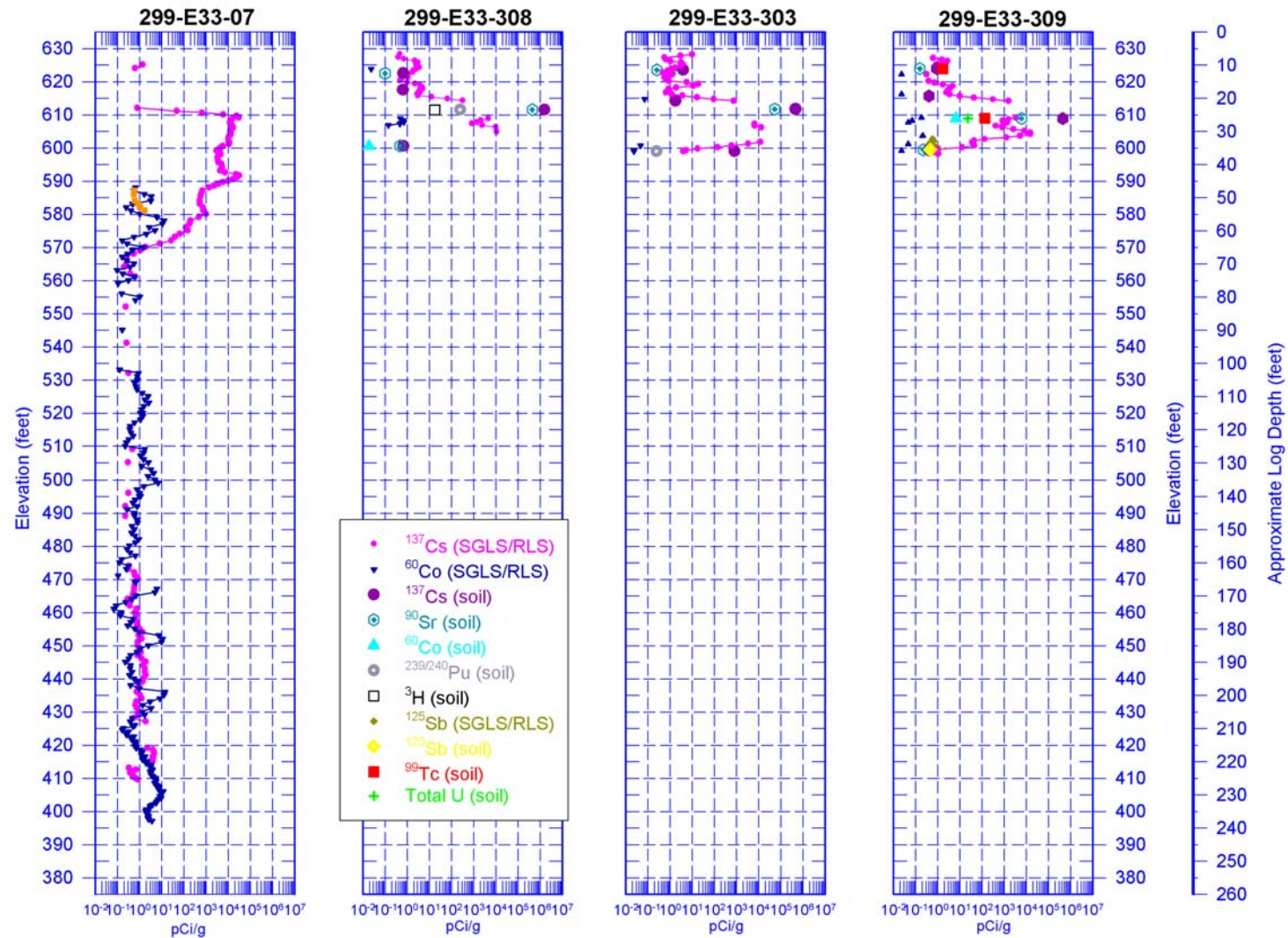


Figure 20. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-50 Crib

216-B-57 Crib

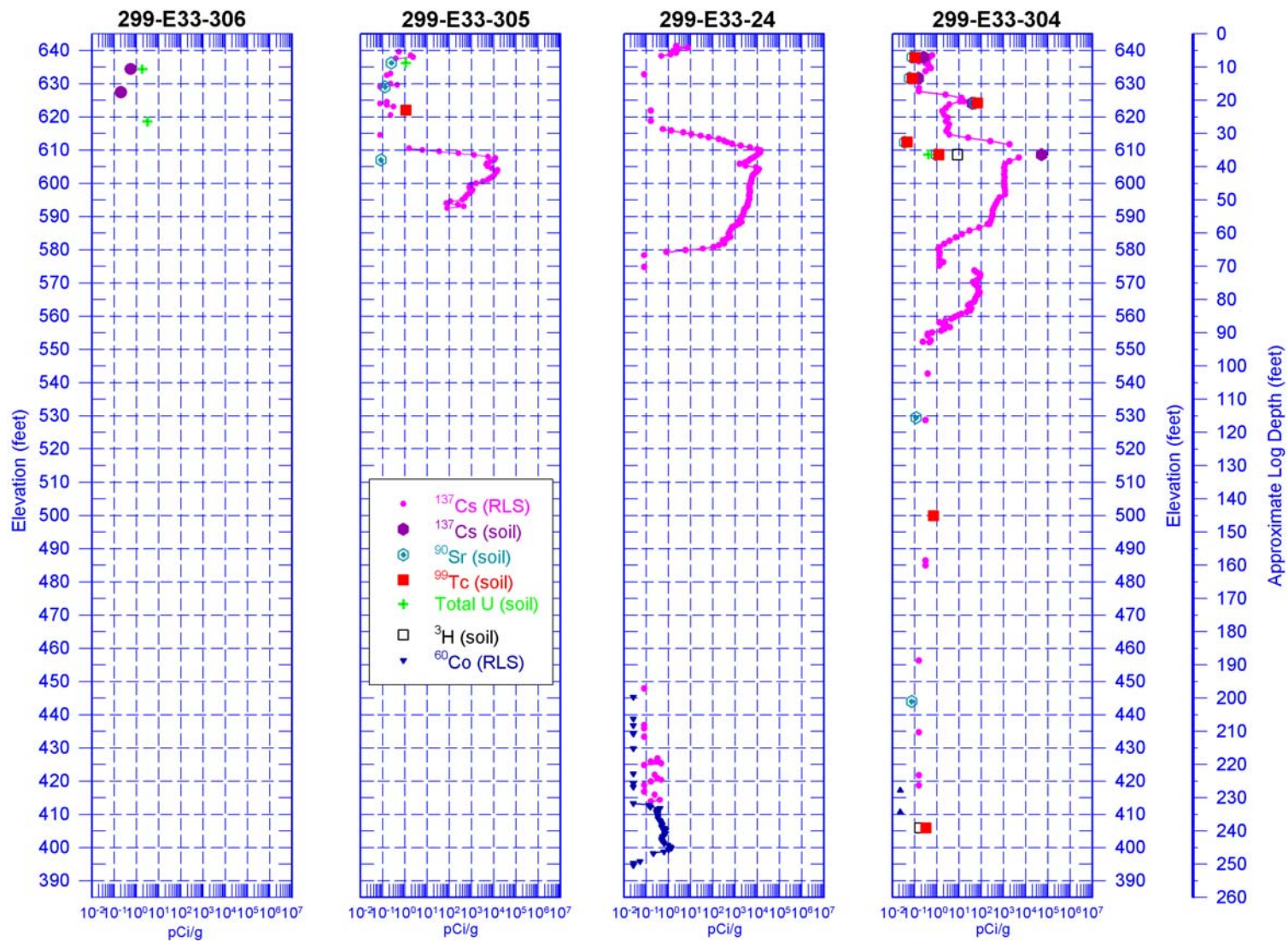


Figure 21. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-57 Crib

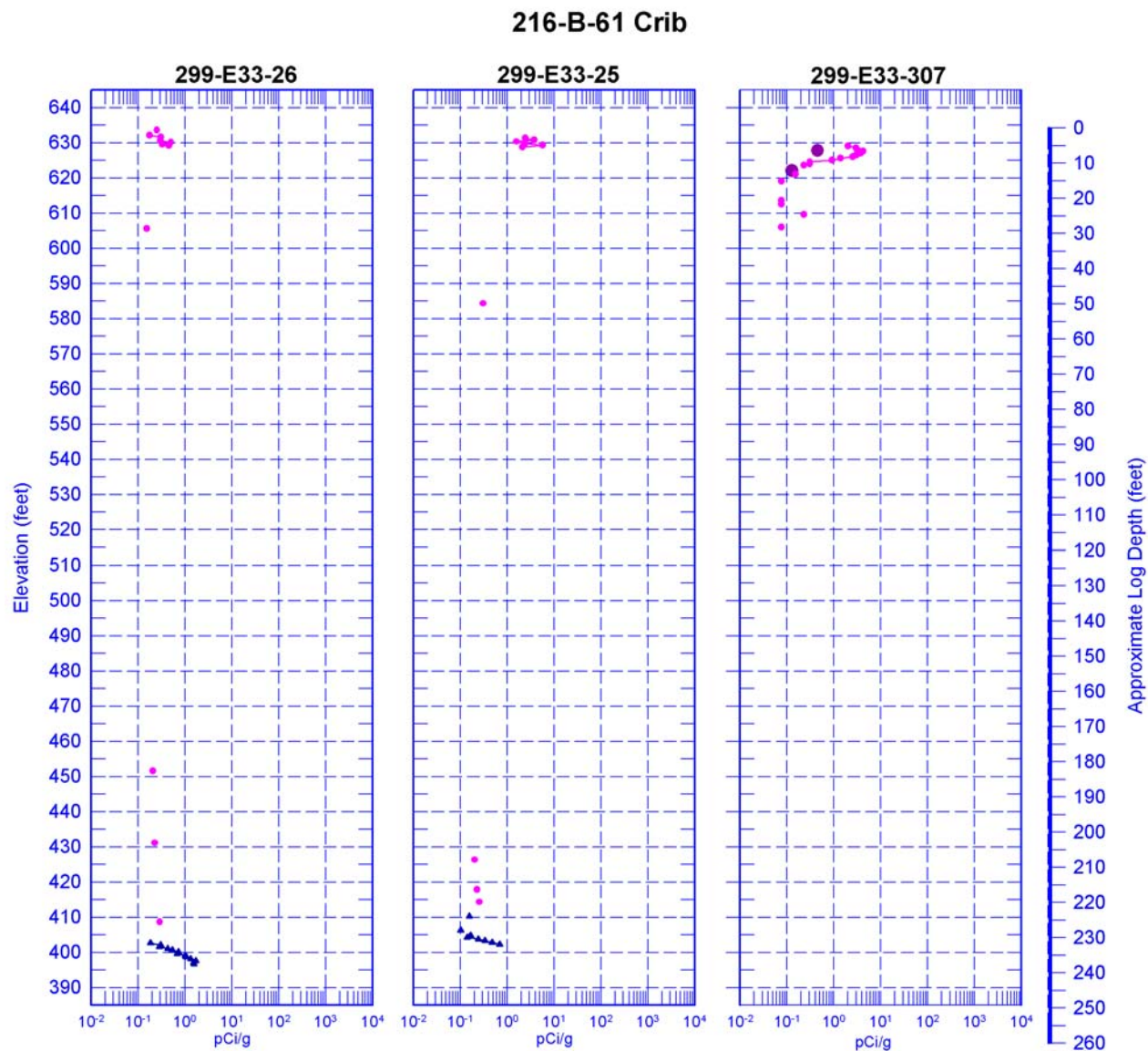


Figure 22. Correlation Plot of Man-Made Contamination Around Boreholes Associated with the 216-B-61 Crib

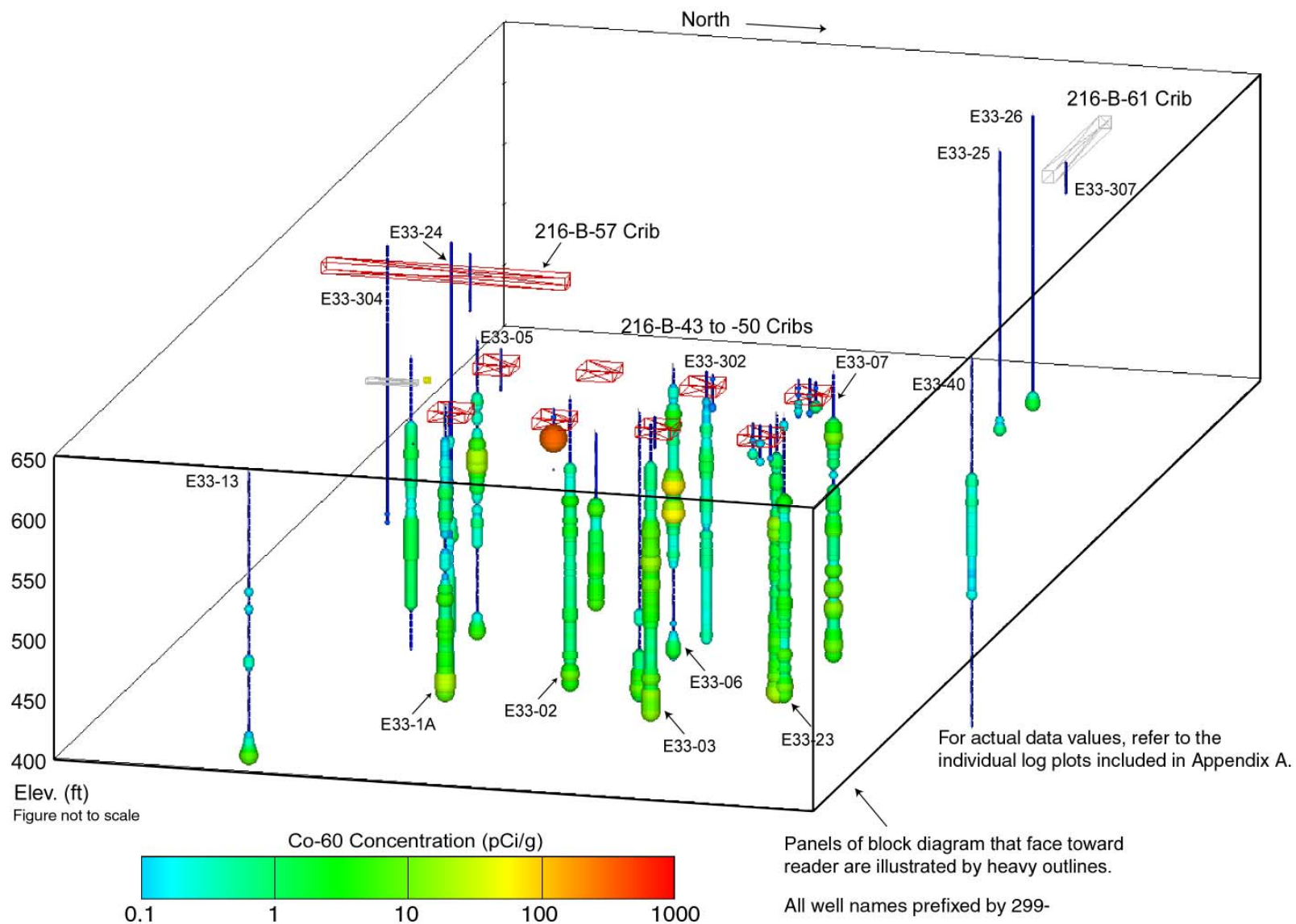


Figure 24. Visualization of the ^{60}Co Data Acquired at the 216-B-43 to -50, -57, and -61 Crib

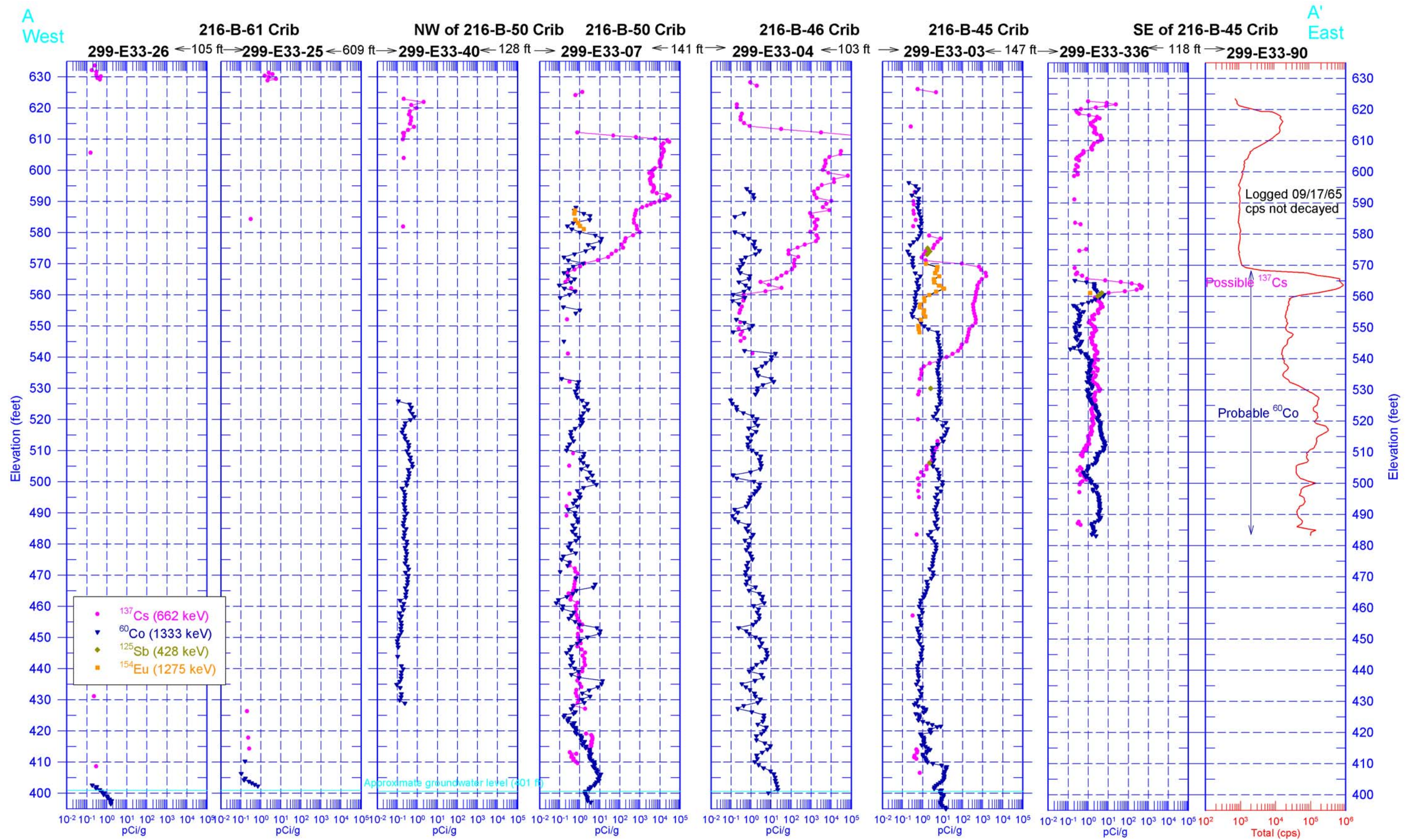


Figure 25. Cross Section A-A' Showing Contamination Along the BY Crib

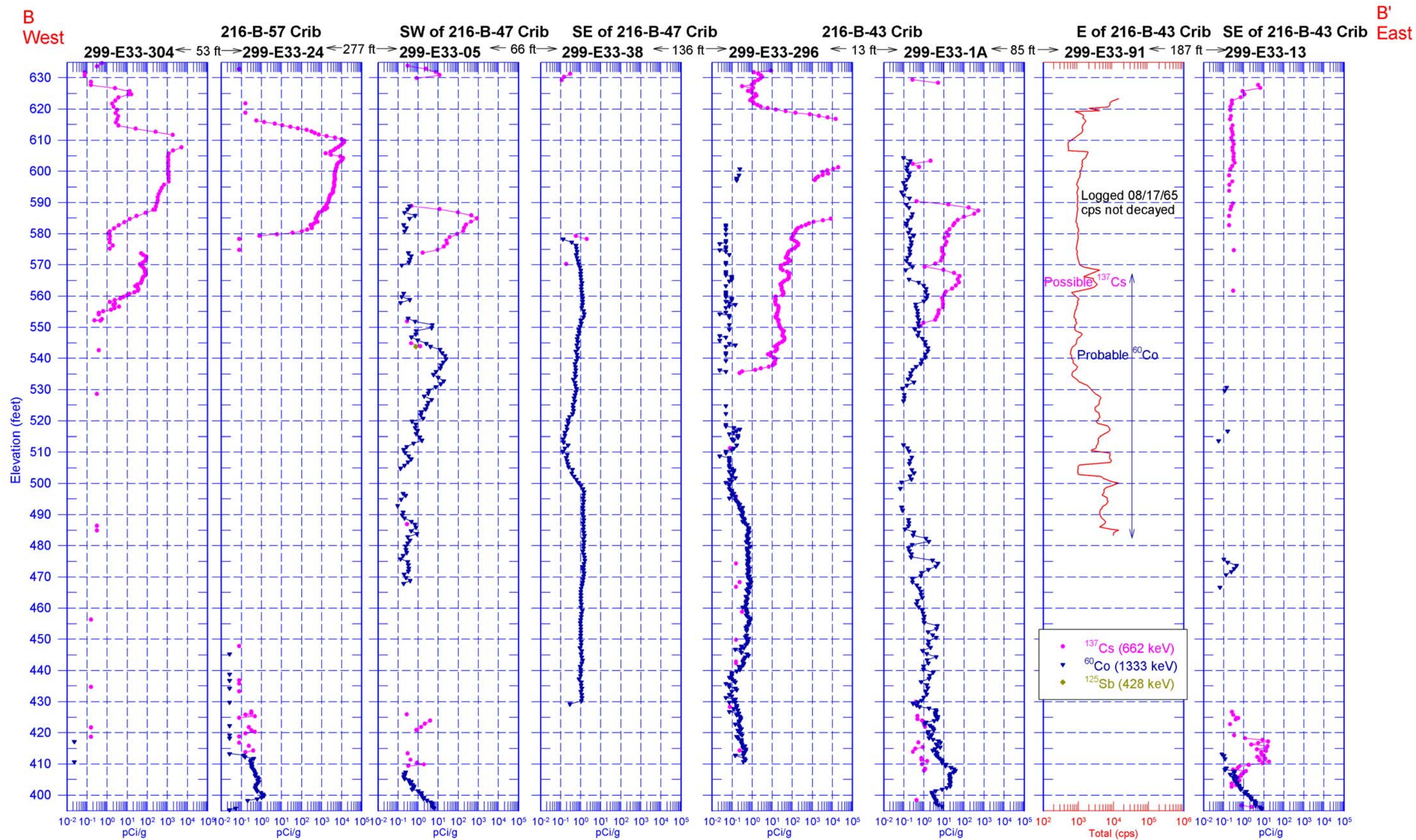


Figure 26. Cross Section B-B' Showing Contamination Along the BY Crib

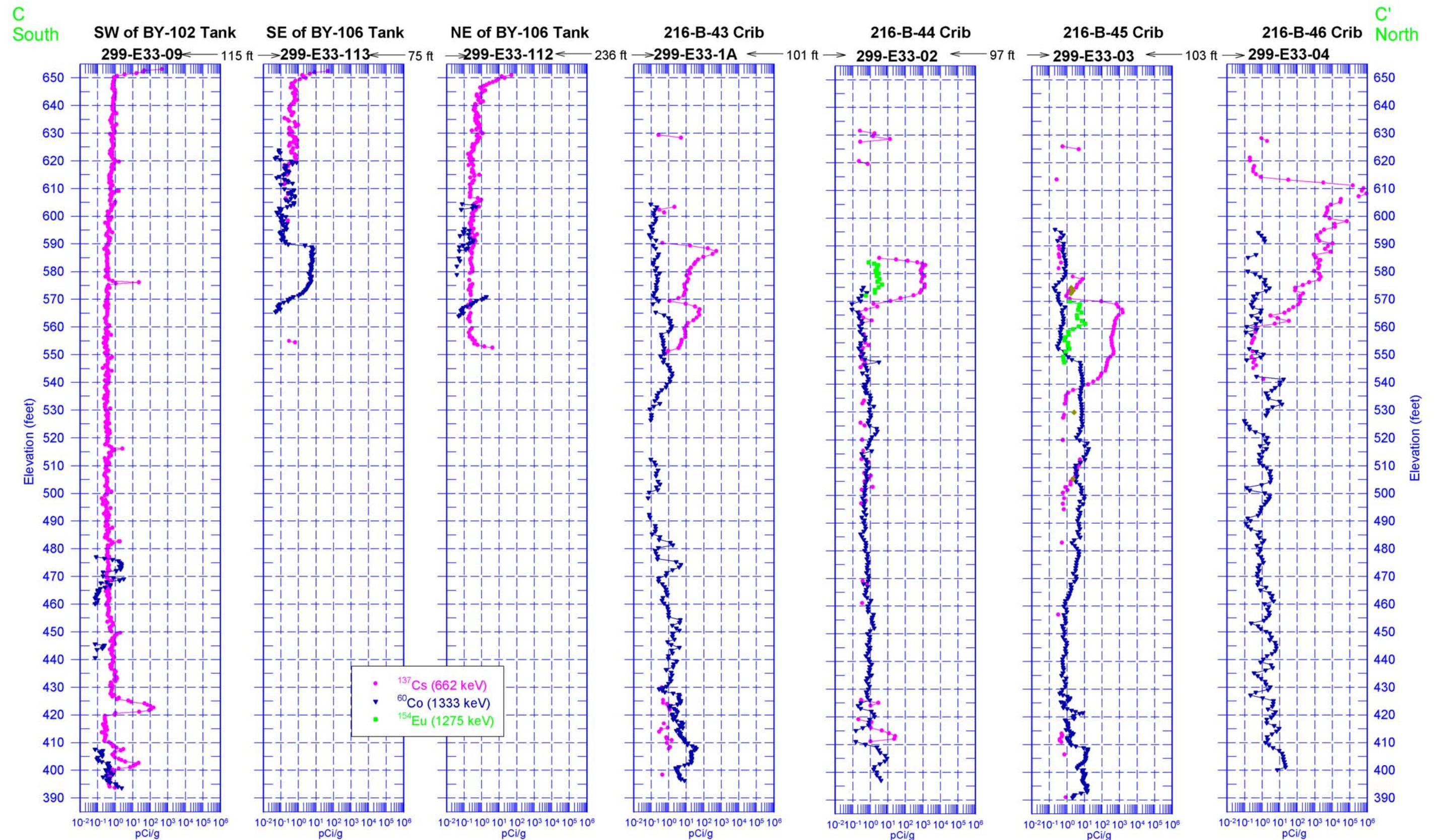


Figure 27. Cross Section C-C' Showing Contamination Along the BY Crib

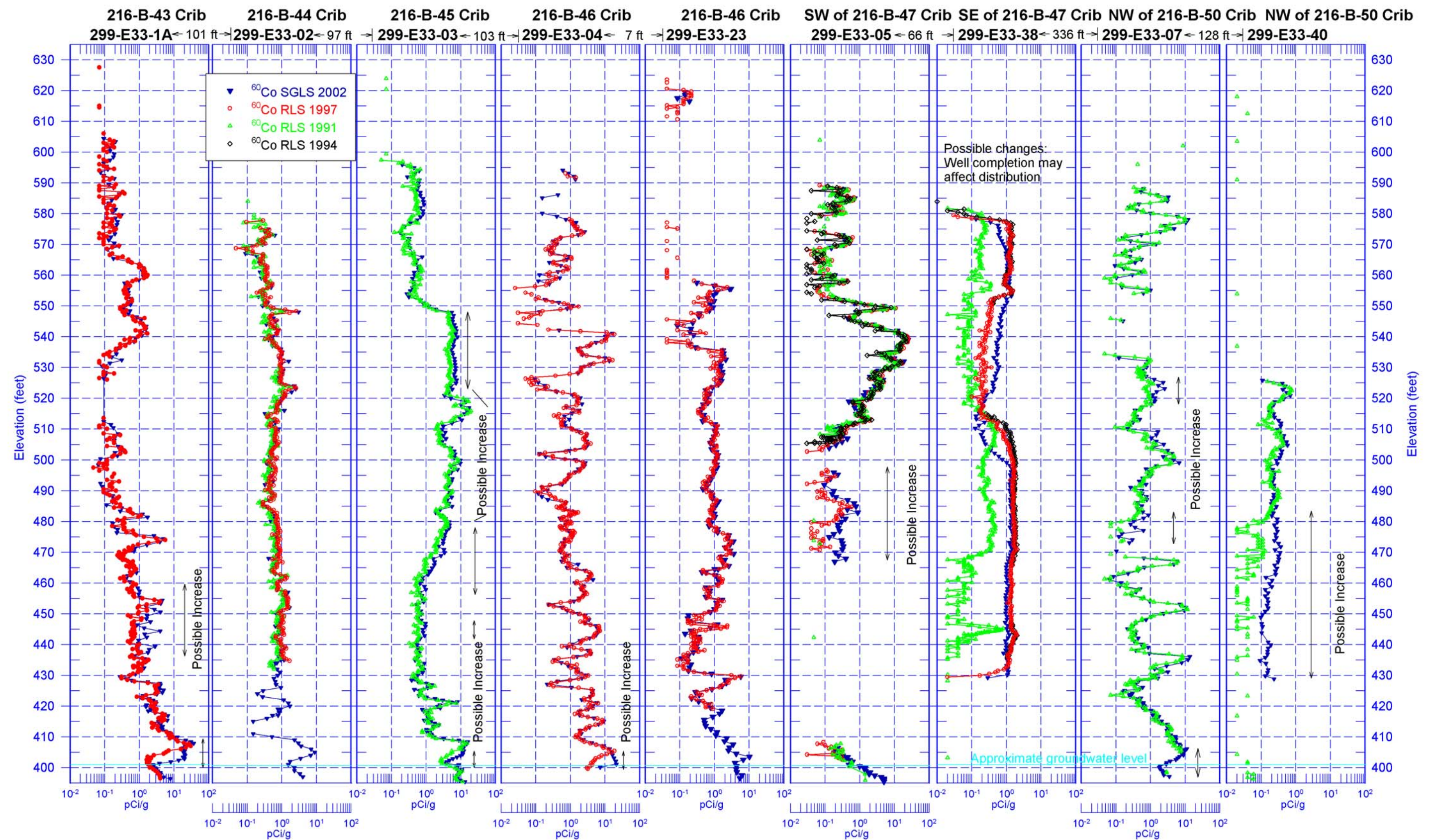


Figure 28. Comparisons of ^{60}Co Concentrations Between 1992 and 2002 in Nine Boreholes in the Vicinity of the BY Crib

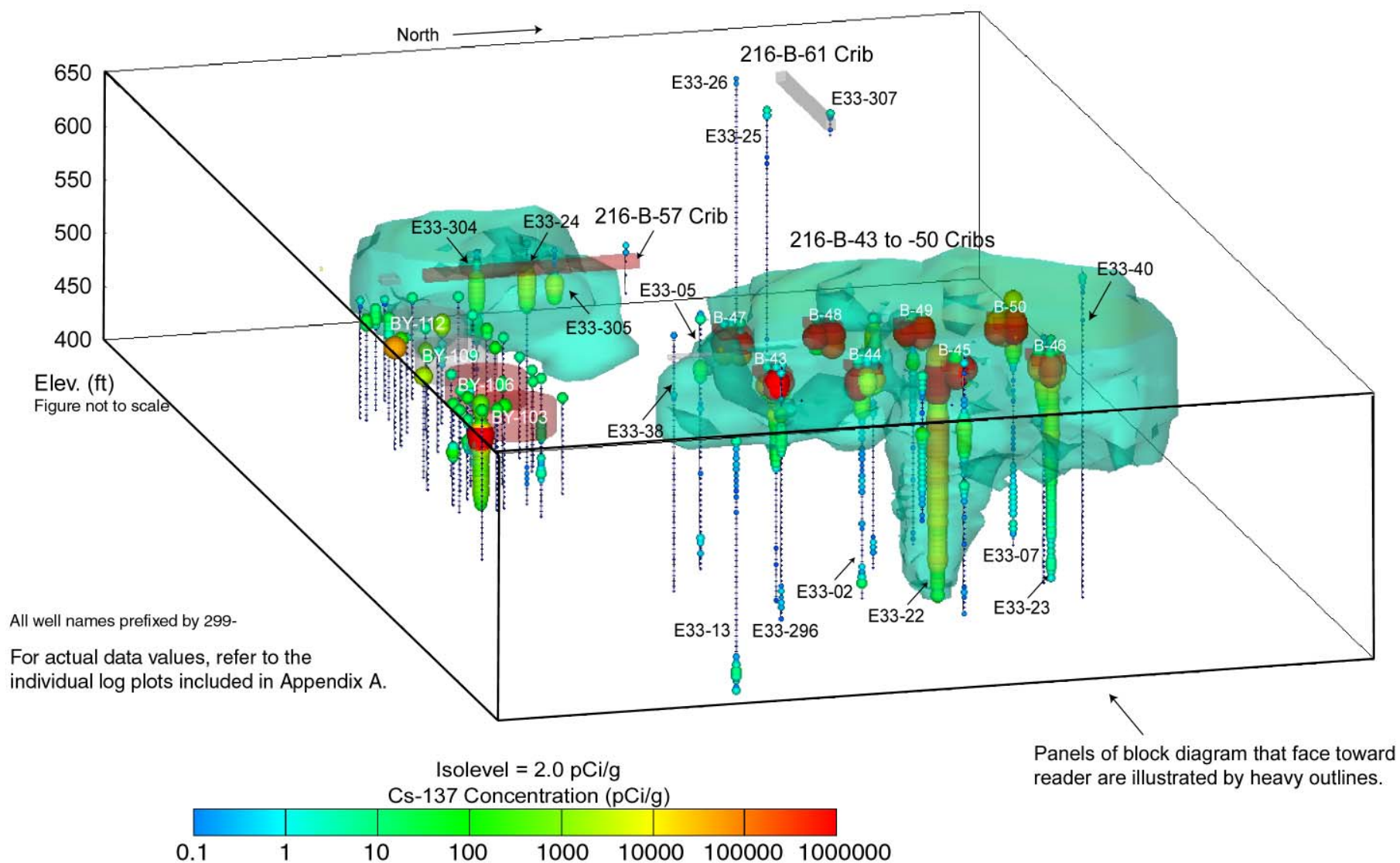


Figure 29. Visualization of ^{137}Cs Contamination in the Vicinity of the BY Crib

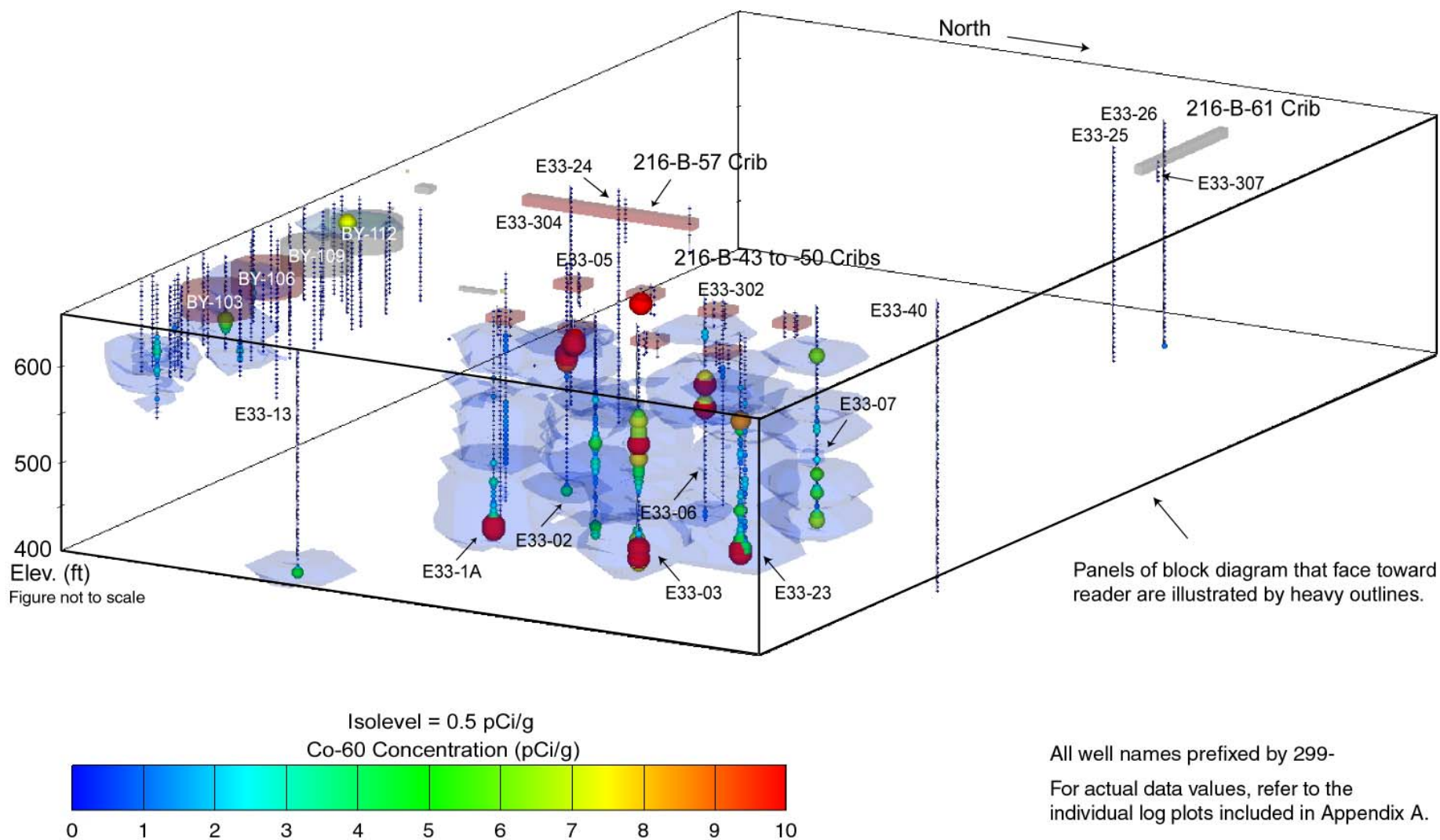


Figure 30. Visualization of ^{60}Co Contamination in the Vicinity of the BY Crips

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Appendix A
Spectral Gamma-Ray Logs for Boreholes and Wells
in the Vicinity of the 216-B-43 to -50, -57, and -61 Cribs
and Adjacent Sites

(included on accompanying CD-ROM)